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THE RELATIONSHIP BETWEEN TOTAL CLOUD LIGHTNING BEHAVIOR AND RADAR DERIVED THUNDERSTORM STRUCTURE

by

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Total cloud lightning detection systems have been in development since the mid–1980s and have been deployed in several areas around the world. Previous studies on total cloud lightning have found intra and inter-cloud lightning (IC) tend to fluctuate significantly during the lifetime of thunderstorms. Prior studies have primarily focused on the electrical characteristics of thunderstorms, thunderstorm development and life cycle theory, but they do not provide much help to the operational meteorological community as they fail to link lightning characteristics to currently used radar interrogation techniques. Studies have indicated lightning jumps tend to be closely linked to changes in the vertical integrated liquid (VIL) reading on the National Weather Service's Weather Surveillance Radar–1998 Doppler (WSR–88D) systems and lightning holes tend to be associated with a bounded weak echo region (BWER) on the WSR–88D. More recent studies have attempted to mathematically classify a lightning jump but are still years away. This study builds off previous results and takes a more aggressive look at total cloud lightning and its relationship to the WSR–88D derived signatures currently used to determine a thunderstorms severity. Lightning and thunderstorm data from the Dallas-Fort Worth, Texas and the Tucson, Arizona areas from 2006–2009, was used to relate lightning to other thunderstorm parameters. A relationship between total cloud lightning behavior and currently used radar interrogation techniques was found indicating lightning jumps can be classified into three different types. Two types show preponderance for a specific type of severe weather event and lightning behavior while the third show no preference. These findings are of significant interest to the operational meteorological community and in some case can be put to immediate use.

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THE RELATIONSHIP BETWEEN TOTAL CLOUD LIGHTNING BEHAVIOR AND RADAR DERIVED THUNDERSTORM STRUCTURE

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ABSTRACT

Total cloud lightning detection systems have been in development since the mid–1980s and have been deployed in several areas around the world. Previous studies on total cloud lightning have found intra and inter-cloud lightning (IC) tend to fluctuate significantly during the lifetime of thunderstorms. Prior studies have primarily focused on the electrical characteristics of thunderstorms, thunderstorm development and life cycle theory, but they do not provide much help to the operational meteorological community as they fail to link lightning characteristics to currently used radar interrogation techniques. Studies have indicated lightning jumps tend to be closely linked to changes in the vertical integrated liquid (VIL) reading on the National Weather Service's Weather Surveillance Radar–1998 Doppler (WSR–88D) systems and lightning holes tend to be associated with a bounded weak echo region (BWER) on the WSR–88D. More recent studies have attempted to mathematically classify a lightning jump but are still years away. This study builds off previous results and takes a more aggressive look at total cloud lightning and its relationship to the WSR–88D derived signatures currently used to determine thunderstorm severity. Lightning and thunderstorm data from the Dallas-Fort Worth, Texas and the Tucson, Arizona areas from 2006–2009, was used to relate lightning to other thunderstorm parameters. A relationship between total cloud lightning behavior and currently used radar interrogation techniques was found indicating lightning jumps can be classified into three different types. Two types show preponderance for a specific type of severe weather event and lightning behavior while the third show no preference. These findings are of significant interest to the operational meteorological community and in some case can be put to immediate use.

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I. INTRODUCTION

Lightning is one of the foremost aspects of operational thunderstorm forecasts that are a challenge to predict accurately and with as much lead time as possible. Lightning presents significant risk to life and property. Due to the risk lightning presents, many outdoor operational activities, especially aircraft fueling, must be suspended when lightning is expected. In order to forecast lightning occurrence and severe weather phenomena, a firm understanding of lightning is required, along with a good lightning detection system.

In order for lightning to occur, electrification of the storm cloud must take place. The electrification process has been found to be particularly sensitive to updraft strength of the developing and/or mature thunderstorm by affecting flash rates (Baker et al. 1995, Williams et al. 1999). In particular, the electrification process is most active near the freezing level of the thunderstorms (Uman 1987; Williams et al. 1999; Hodapp et al. 2008).

A charge separation process is required, which Williams et al. (1999) explains, is a process having the greatest affect in the mixed phase layer of thunderstorm. This is where rising liquid hydrometeors collide with the heavier falling frozen hydrometeors like graupel and hail. When the heavier frozen hydrometeors collide with the lighter liquid hydrometeors, the interaction negatively charges the falling frozen hydrometeors and positively charges the rising liquid hydrometeors. The updraft is stronger than the natural attraction forces of the two opposite charges and the two charges are then separated. This process is one of two electrification theories proposed by Uman (1987), which he called the precipitation theory. The other theory was called convective theory, which suggests the electrification process occurs in bulk with the existing electric charge throughout the Earth's surface. This accumulated charge in the lower atmosphere is then separated from the opposite charge at the surface by advective forces acting on the cloud field. The strongest argument for this theory is the observation that lightning occurs in clouds failing to reach the freezing level (Uman 1987).

Past studies by Kuettner et al. (1981) have also given credence to the precipitation theory of Uman (1987) but focused on inductive and non-inductive electrification processes in developing and/or mature thunderstorms. The non-inductive process focuses on the electro-chemical or thermoelectric properties of the colliding solid and liquid particles and the resultant charge separation that occurs. The inductive processes focus on the pre-existing external electric fields, which are separated by the resulting collision and separation process of the hydrometeors (Kuettner et al. 1981). Both theories presented by Uman (1987) and Kuettner et al. (1981) demonstrate the mix-phase layer of a thunderstorm is the most active area of the cloud where charge separation and electrification occurs. Deierling et al. (2005) demonstrated the charge separation in a number of past studies that indicate the presence of ice is not only critical to the electrification process, but the size the frozen hydrometeors and proportion of the different sizes of the hydrometeors will have a profound effect on the process. In most cases, large amounts of graupel and hail will allow more electrification while more ice crystals with lower amounts of graupel and hail can inhibit electrification (Deierling et al. 2005).

A. LIGHTNING DETECTION

The first lightning detection system used visual optics to detect the visible flash of lightning. The optical system, although useful in some circumstances had significant limitations. The two main limitations were it only had a short line of sight detection capability, and more significant, was the system's inability to detect lightning obscured by rain/hail shafts from the parent thunderstorm (Pierce 1977). The discovery of the radio frequency (RF) noise created by lightning flashes/strokes, allowed triangulation of the RF noise to not only detect but locate the flash. The first effective lightning detection system of RF triangulation utilized four sensors that monitored RF noise in the very low frequency (VLF) band of 3–30 kHz and the low frequency (LF) band of 30–300 kHz. The RF triangulation system proved itself to be far superior to the optical system of the day (Pierce 1977). The RF triangulation method is still used today and is employed by the National Lightning Detection Network (NLDN). The RF triangulation system's main limitation is that it can only detect the cloud-to-ground lightning strokes (Pierce 1977;

Williams et al. 1999; Shao et al. 2006). Pierce (1977) also noted thunderstorms also produce a large amount of RF noise in the high frequency (HF) band of 3–30 MHz and the very high frequency (VHF) band of 30–300 MHz, but this noise was not associated with the cloud-to-ground (CG) strokes. High HF and VHF RF noise was especially noted during tornadic storms, which tended to have very powerful VHF RF noise emissions (Pierce 1977). The fact the NLDN system could only detect CG strokes, and past studies have noted powerful VHF noise from tornado producing thunderstorms led to the development of lightning detection systems to detect the in-cloud or intra-cloud and inter-cloud lightning (IC) (Pierce 1977; Demetriades 2007). In this study, the in-cloud, intra-cloud and inter-cloud will be used interchangeably to mean all three types of IC lightning. The first system to detect IC was the Los Alamos Sferic Array (LASA) developed by the Los Alamos National Laboratory and New Mexico Tech in 1998 (Shao et al. 2006; Demetriades 2007). This LASA operates in the HF and VHF bands allowing the system to detect the IC lightning. The LASA system was later combined with the capabilities of the NLDN system allowing it to detect both CG and IC lightning. A combined IC and CG lightning detection system defines the total cloud lightning. This study will focus on this aspect of the lightning detection.

B. PAST TOTAL CLOUD LIGHTNING STUDIES

Since the advent of total cloud lightning detection, there have been many studies using total cloud lightning detection systems. There have been some studies examining the characteristics of total cloud lightning. Some studies have focused on the total lightning structure of the thunderstorms concentrating on the polarity structure of thunderstorms (Goodman et al. 1988; Montanya et al. 2008; Shao et al. 2006).

Goodman et al. (1988) attempted to determine the characteristics between IC and CG lightning. Goodman's study was very ambitious at the time as an effective total cloud lightning system had not been developed yet. Goodman utilized the conventional NLDN system and a specially equipped U–2, which overflew the thunderstorms. His study found severe thunderstorms producing hail and tornadic activity tended to produce large amounts of IC and a significant number of positively charged CG lightning

(Goodman et al. 1988). In later studies, total cloud lightning systems were used to study powerful lightning strokes that often had ionospheric reflections called "narrow bipolar events". These narrow bipolar events were noted to frequently be positive in polarity and be a possible indicator of thunderstorm strength (Shao et al. 2006). Other studies have focused on the rapid increase in IC lightning prior to the onset of severe weather to explain the changing structure of severe thunderstorms (Montanya et al. 2008).

Previous studies do provide some significant insight into the evolution of thunderstorms helpful in future research. Unfortunately, they do not provide any real value to the operational forecaster, and do not provide the operational forecaster any new usable tool to identify severe or tornadic activity more efficiently than current operational methods. Montanya et al. (2008) does shed a little insight into possible operational uses of the system as the study strongly indicates that a significant increase in IC and/or CG lightning tends to be a precursor to severe weather onset. Montanya however, does not evaluate which storm parameters currently used in operational forecasting are related to these increases and, thus, it is not as helpful in the operational environment as it could have been.

Other studies have focused more on the thunderstorm structure and the accompanying severe weather associated with this type of activity. More importantly, these studies highlight possible key changes in a thunderstorm's total lightning characteristics that potentially open up new and faster ways of interrogating severe storms (Williams et al. 1999; Goodman et al. 2005).

The studies by Williams et al. (1988,1999), Goodman et al. (2005) and Steiger et al. (2007a,b) have focused on either the storm structure and how it relates to total cloud lightning, or what changes in total cloud lightning relate to the sensible weather on the ground. More specifically, they attempt to determine the time between the change in total cloud lightning and the occurrence of severe weather on the ground. One of the first studies to do this was in 1999 using the Lightning Imaging Sensor Demonstration and Display (LISDAD) in central Florida by Williams et al (1999). Williams found that IC does not coincide with max cloud top height (echo top), but does with max reflectivity in the mixed phase layer. Changes in IC would occur abruptly with no immediate change in

the radar return (Williams et al. 1999). The abrupt changes in IC behavior indicates there is a delay in the sensible weather on the ground from the time of change in the IC lightning activity. Additionally, sudden increases in flash rates or lightning jumps have been observed in severe thunderstorms and tend to precede severe weather occurrences on the ground by as much as 30 minutes (Williams et al. 1999). Later, Goodman et al. (2005) indicated other IC lightning characteristics tend to be closely linked to other thunderstorms structures. In some cases an area of reduced or no lightning called lightning holes, are nearly always associated with a bounded weak echo region (BWER) radar signature and were usually detected using total cloud lightning sooner than current radar technologies (Goodman et al. 2005).

The characteristics of lightning jumps and lightning holes, and how they relate to the structure of thunderstorms presents a tantalizing possibility for new and more effective tools in the severe weather warning process. Prior studies found tendencies for lightning jumps and holes to be directly related to various severe weather events and distinctive radar characteristics. By combining total cloud lightning with current radar systems, the potential for new and more efficient severe weather interrogation tools exists for the operational forecaster. Unfortunately, past studies of these characteristics have failed to evaluate how these changes in total cloud lightning relate to established thunderstorm interrogation techniques. The fact that total cloud lightning detection systems have yet to be closely examined for their relationship to currently used radar interrogation techniques presents a problem to the United States Air Force (USAF) and the National Weather Service (NWS). The goal of this thesis is to discover the relationships (if any) between total cloud lightning and radar derived structures with the hope they can be applied in an operational setting in the future.

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II. BACKGROUND

A. TOTAL CLOUD LIGHTNING

Total cloud lightning refers to all lightning in and between thunderstorms including IC and CG lightning activity. The NLDN uses sferics and the VLF radio band to detect the CG strokes (Pierce 1977; Williams et al. 1988, 1999). The NLDN was established many years ago and has proven to be a useful tool to forecasters. NLDN cannot detect the IC lightning flashes. IC lightning can be detected through sferics using the HF and VHF radio band. A lightning detection system using the HF and VHF bands was first deployed operationally by New Mexico Tech at the National Space Science and Technology Center (NSSTC) Alabama in 2001–2003 and has been utilized operationally by the Huntsville NWS, (Demetriades 2007). The forecasters at Huntsville noted a sudden increase in total lightning activity prior to the onset of severe weather. These lightning jumps were noted to occur as much at 30 minutes prior to the occurrence of severe weather (Demetriades 2007). The observation is confirmed in studies by Williams et al. (1999) and Goodman et al. (2005). The observations from prior studies and the Huntsville site led to the development of the total cloud lightning systems developed by Vaisala Inc. to be deployed in various parts of the world including the Kennedy Space Center, Florida (KSC), Washington D.C. (KIAD), Houston, Texas (KEFD), Paris, France (LFPG), Dallas-Fort Worth, Texas (KDFW) and Tucson, Arizona (KTUS). This study will focus solely on data from the KDFW and KTUS sensor sites.

Williams et al. (1999) observed a tendency for increased IC lightning activity to precede downbursts. Since downbursts require a strong updraft prior to the formation of the downburst, an increase in IC lightning indicates an increase in the strength of the corresponding updraft of the thunderstorm and the thunderstorm itself. The updraft of the thunderstorm must pass through the mixed phase layer. The mixed phase layer is known to be an area of significant charge separation and/or electrification indicating the updraft would be the primary area for IC lightning jumps (Uman 1987; Williams et al. 1999). Other studies have indicated the main area of the hail shaft is an area where IC lightning does not occur and is more likely to be on the edges of the main updraft and/or hail shaft

(Steiger et al 2007a; Boussanton et al. 2007). Both studies indicate the increasing in IC lightning activity occur in the mixed phase layer of the thunderstorm (Uman 1987; Williams et al. 1999; Steiger et al. 2007a; Boussanton et al. 2007).

Thunderstorms are generally considered to have a dipole structure with the negative charge at the cloud base and the positive charge at higher altitudes. An increase in the strength of the main updraft would disrupt this system. As the main updraft increases in strength, it will raise the negatively charged region closer to the positively charged region aloft. As the two regions come closer together, the IC lightning activity rapidly increases. If the updraft is strong enough, the center of the updraft will become void of lightning activity as it becomes saturated with a like charge, usually negative, brought higher by the updraft. As such, the increased IC lightning will concentrate around the edge of the updraft (MacGorman et al. 2002). If the updraft becomes intense enough, it can produce an inverted dipole structure within the storm or a multi-pole structure (- +, - +) producing continuous IC lightning (Montanya et al. 2008). The sudden increase in IC lightning activity and areas of the thunderstorm becoming void of lightning, are some of the total cloud lightning characteristics NWS operational forecasters at KDFW, KTUS and Air Force Weather Forecasters (AFWF) at Davis-Monthan Air Force Base (DM AFB), Arizona have noted when using the total cloud lightning data. These observations and past studies indicate this sudden increase in IC lightning activity or lightning jumps are directly related to the strength of the main updraft of the thunderstorm as measured by the WSR–88D reflectivities.

B. CHARATERISTICS AND SEVERE WEATHER

Studies by MacGorman et al. (2002), Steiger et al. (2007a) and Montanya et al. (2008) have clearly shown lightning jumps are directly related to the strength of the main updraft of the thunderstorm as measured by the WSR–88D reflectivities. Since the main updraft of the thunderstorm is a key indicator of the potential for severe weather, lightning jumps are likely to be precursors to severe weather on the ground (Williams et al. 1999; Steiger et al. 2007a). Since the development of the total cloud lightning detection systems, there have been several studies to determine its usefulness and the

reliability of lightning jumps to predict severe weather. Studies by Steiger et al. (2007a) indicate lightning jumps occurring between 5–30 minutes prior to the occurrence of severe weather on the ground with super cell thunderstorms. Goodman et al. (2005) indicates a similar result with lightning jumps in pulse storms occurring on average 12 minutes prior to severe weather occurring on the ground. Williams et al. (1999) also shows this correlation where lightning jumps occurred 1–15 minutes prior to severe weather on the ground and lightning jumps preceded severe hail events by seven minutes on average.

Not all studies indicate consistent results of lightning jumps occurring prior to severe weather. Consistency has only been noted for super cell, pulse and non-severe thunderstorms that are individual systems (either single or multi-cell systems). In super cell cases (single or multi-cell storms) lightning jumps are consistently noted to be concentrated around the main updraft of the storms. In the case of Mesoscale Convective Systems (MCS) or Mesoscale Convective Complexes (MCC), the lightning jumps tended to occur during or after the severe weather event (Steiger et al. 2007b). Two possibilities may explain the difference between the cases: 1) the new developing thunderstorms along the gust front initiate lightning activity as their updrafts develop but in an orientation similar to the gust front and 2) the strong winds of the MCS advect the charged cloud and precipitation particles ahead of the parent storm and the IC lightning then initiates in these advected areas (Steiger et al. 2007b). The second possibility suggests the lightning jump cannot be detected as the many different updrafts within an MCS force the charged cloud and precipitation particles out of their normal locations. The updrafts in a MCC or MCS are more complex than a super cell ,which causes the increase in IC lightning to occur over a much wider area and may not be detectable as a lightning jump as the increase in IC activity is much more dispersed. This dispersion of the increased IC lightning in a MCC/MCS indicates there is insufficient charge separation near a single updraft. This wider area of dispersion also may make it more difficult to detect sudden increases in IC lightning activity as it may be confused with an expanding storm rather than an intensifying storm. Another study by Hodapp et al. (2008) makes a similar hypothesis indicating advective forces in the stratiform region as the reason for displacing

the charged particles away from the updraft. This means conventional radar techniques will detect the increase in intensity before total cloud lightning can detect concentrated jumps in IC activity.

The consistency of the lightning jumps with the single, multi-cell and super cell cases open up the possibility for total cloud lightning to provide a new interrogation tool for operational forecasters. Past studies, however, fail to provide a link between the changes in total cloud lightning characteristics and current established severe storm interrogation procedures employed by the NWS and AFWF. Only a few past studies have looked into direct links between lightning and current severe storm interrogation techniques. Perez et al. (1997) was one of the first to indicate a direct link between IC and CG and tornadic activity during the 13 March 1990 Hesston, Kansas F5 tornado event. Perez noted that CG lightning significantly increased just prior to tornado touchdown but then came to a halt for nearly 10 minutes after touchdown. Additionally, IC lightning appears to have a greater correlation in tornado genesis but also indicates that in approximately 50 percent of violent tornado activity (F4–F5), the CG drops dramatically or ceases altogether at the time of tornado touchdown (Perez et al. 1997). The overall peak CG flash rate was shown to be more related to the lifetime of the tornado with no predictable tendency (Perez et al. 1997). Perez's study indicates a relationship between total cloud lightning and severe weather but the tools at that time did not exist to fully examine the relationship. This was later noted by Steiger et al. (2007a) although, other studies have shown using CG rates as a precursor to tornadic activity has produced varied results possibly indicating that CG rates may be regionally dependent (Perez et al. 1997; Carey and Rutledge 2003).

As previously stated, lightning holes have been shown to be "nearly always associated with a BWER" (Goodman et al. 2005). The identification of a BWER is one of the storm structures that is part of storm interrogation in the operational setting. Goodman's paper only looked at this in the case of tornadic activity, which limits its usefulness to the operational meteorological community. A later study by Steiger et al. (2007a) confirmed Goodman's finding but went a little further. Steiger (2007a) noted the lightning height showed the strongest correlation with the vertical integrated liquid (VIL).

VIL is another parameter commonly used by the operational community in thunderstorm interrogation. Steiger also examined maximum reflectivity, several hail indices from the Weather Surveillance Radar-1998 Doppler (WSR–88D), and VIL. A strong correlation between VIL and total cloud lightning, strong enough to be considered statistically significant, was found (Steiger et al. 2007a). It should be noted though this can only be applied to single or "stand-alone" super cells or other severe thunderstorms and not to MCS or MCC. In the MCC/MCS cases, the IC and CG lightning peaks showed significant variability in relation to the severe weather event to the point where no significant relationship between severe straight line winds and total lightning could be found (Steiger et al. 2007b; Hodapp et al. 2008).

The most recent study, at the time of this writing, tested some mathematical algorithms to identify lightning jumps in real time. This study tested four different algorithms, two of which used an average–based approach to compare the average to the rate of change in the lightning counts and the other two took a more statistical approach where the standard deviations of lightning activity was compared to the rate of change in the flash rate (Schultz et al. 2009). The algorithms Schultz used showed some significant promise in aiding the forecaster to identify lightning jumps prior to severe weather events. Although algorithms show significant promise ,they have a high false alarm rate and even fail to identify lightning jumps prior to some severe events, including tornados. This was a predicted result by Steiger et al. (2007a) as the formula used may be too simple. The algorithms used by Shultz et al. (2009) will need more refinement. When the refinement is completed and re-tested, these algorithms present a possibility of having automated real-time lightning jump identification in the future. As a result, the application of an automated lightning jump identification tool to aid the forecaster is still years away (Shultz et al. 2009). Schultz does not directly relate the nature of lightning jumps to the corresponding storm structures that are currently used in operational settings. Making a direct comparison between lightning jumps and radar derived thunderstorms structures used in an operational setting may aid in reducing the false alarm rate.

These previous studies suggest some new possibilities for operational forecasters to use lightning tools along with identification of BWER, changes in VIL and maximum reflectivity to improve severe storm forecasts. These previous studies, however, do not examine several other common interrogation parameters in severe storm forecasting in relation to lightning activity to allow use by operational forecasters. This thesis makes a robust examination of total cloud lightning and its relationship (if any) with commonly used radar interrogation parameters. These interrogation parameters include; weak echo regions (WER), bounded weak echo regions (BWER), mesocyclone detection (MESO), rapid changes in the 55DBz height, rapid changes in maximum reflectivity, rapid changes in VIL, rapid changes in VIL density and wind gust potential (WGP). The last two parameters are heavily used by AFWF today and are empirically derived from the USAF Technical Note 98–02. Additionally, these parameters will be compared to the actual severe weather events and the behavior of the lightning jumps that preceded the events to determine a more robust combined approach to severe weather forecasting.

III. DATA ANALYSIS AND METHODOLOGY

A. SITE SELECTION

The thunderstorms selected for this study originated from two areas of the United States. Both locations were selected for their preponderance for frequent thunderstorms, vigorous lightning activity, and their close proximity to a NWS WSR–88D radar system and a total cloud lightning systems. The close proximity to the WSR–88D helped reduce artifact errors in the level III data due to gaps between the scan elevation levels, which occur as the thunderstorm moves further away from the radar. For this thesis, Dallas–Fort Worth (KDFW), Texas and Tucson (KTUS), Arizona were selected. The KDFW site is located in a heavily populated area with a WSR–88D radar system located just to the south of Forth Worth, which places the radar just to the south of the center of a dense Lightning Detection and Ranging II (LDAR II) total cloud lightning detection system. The KTUS site is less populated and has a WSR–88D radar system to the southeast and is also the home of Vasiala Inc's new total lightning LS8000 system. The lower population area of the Tucson area did have the drawback of producing fewer verifiable severe weather events as many areas surrounding the KTUS area are so sparsely populated or completely uninhabited to produce verifiable ground truth.

1. Lightning Detection System Capabilities and Limitations

The LDAR II system at the KDFW site was deployed in late 2004 and has been used in several total cloud lightning studies over the past few years and is used operationally at the NWS office in Fort Worth, Texas. This system employs nine lightning detection sensors detecting both IC and CG lightning. This system detects the radiation pulse from the electrical breakdown processes produced by lightning flashes. It requires a minimum of four (ideally five or more) sensors to detect the flash in order to resolve the flash location. Additionally, this system has a three dimensional capability so the user can look at the detected and examine the flash in all three dimensions. The LDAR II unfortunately, is not a weather-hardened system and is intended for research purposes rather than day to day operational use. The LDAR II is susceptible to rain fade

during times of heavy precipitation and individual sensors can become disabled or impaired causing a brown out condition at times. If more than one sensor becomes impaired or disabled, the LDAR II will cease resolving the IC lightning all together. There were several prospective thunderstorm cases discarded from this study due to this as there was no sure way to resolve the IC lightning pattern for the storm being interrogated.

The LS8000 lightning detection sensor at the KTUS site is a new system deployed in 2007. The main difference between the LS8000 and the LDAR II at KDFW is the LS8000 is a two dimensional system and is weather hardened intended for day to day operations. Since it is a two dimensional system, it only requires four sensors to operate with only two to three sensors required to detect the flash and resolve its location. This system also uses a time of arrival algorithm, much like the current sensors used in the NLDN system. Like the LDAR II, the LS8000 can detect both IC and CG lightning flashes. Unlike the LDAR II system, the LS8000 does not suffer from rain fade or brown out issues due to heavy precipitation. It will detect lightning in all conditions.

Both systems have an effective range of 100km with the LDAR II system sometimes reaching 150km for cases in which all sensors are not affected by rain fade or a brown out event. The close proximity of the WSR–88D radar system to the lightning networks helped reduce the gaps in the scan elevation angles that are inherent with this radar system. This helped reduce artifact errors in the Level III data, especially in VIL, which is particularly susceptible to these errors when the storm is further away from the radar site. The close proximity to the radar site does have the disadvantage of the storm top breaking into the radars cone of silence if the cell is too close. These cases limited the measurement of some of the radar parameters, especially the 55DBz height. Fortunately, only four of the cases studied fell into this category. The vast majority of cases studied were in the optimal range of 15–70 km of the radar site insuring a solid volume scan at each time step.

B. CASE SELECTION

Thunderstorms were selected based on the occurrence of severe weather within each site's range of lightning detection from 2006–2009. Occurrences of severe weather were determined from the NWS local storm reports (LSR) that were obtained from the National Climate Data Center (NCDC). Past studies by Shultz et al. (2009) have noted time and location errors in the LSRs. This thesis also noted some of these same errors. During the course of the data collection and analysis phase, time errors were considered minor enough to disregard but location errors tended to cause more problems. Two cases had to be removed due to large location errors, as there was no way to determine which thunderstorm cell produced the reported severe weather. Even given the known problems with the NWS LSRs, the LSRs on the NCDC's site is the most accessible and accurate available today. For the purposes of this study, a severe weather event is defined at hail of ¾" or greater, wind of 50Kts or greater or the occurrence of a tornado touchdown.

1. Radar Data and Tools

Once the dates of the severe weather events were identified, WSR–88D data was obtained from the NCDC's Hierarchical Data Storage System (HDSS) Web site. Level II and Level III data was obtained for each day a severe weather identified. The radar data was analyzed using NCDC's Weather and Climate Toolkit. The toolkit is an easy but rather powerful program allowing the user to analyze and interrogate past WSR–88D data on a wide variety of platforms including Windows PCs and Macs. The toolkit is capable of interrogating past data at all levels from the Level II data and provides interpretation and display of nearly all the available Level III data as well. This set up allows the user to interrogate past storm data in much the same way as an operational forecaster would on an Open Principal User Processor (OPUP). Figure 1 shows a Level III display of a convective system that was later identified as a mesocyclone. The much more versatile and powerful Warning Decision Support System–Integrated Information (WDSS–II) interrogation program jointly developed by the National Severe Storms Laboratory (NSSL) and the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) at

the University of Oklahoma was considered for use, but circumstances beyond the author’s control precluded the use of this software.

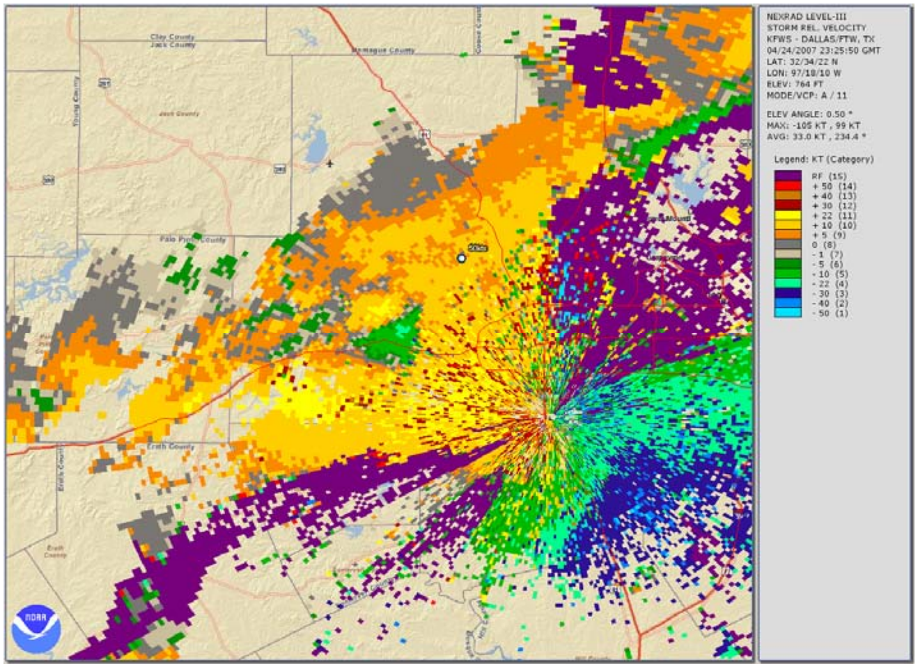

Figure 1. Level III Storm Relative Velocity Display

The use of Level III data was the primary source of detecting changes in the VIL, Echo Tops, Mesocyclone and Tornado Vortex Signatures (TVS) signatures of individual storms. The rules used to identify these features were governed by the NWS Federal Meteorological Handbook No. 11 Part D (FMH–11). The FMH–11 has been rigorously updated through the years and is considered the standard for radar interrogation of thunderstorms. The copy used for this thesis was updated in February 2006 and was used to keep this study as relevant to operational settings as possible. The FMH–11 standards were also used to identify the changes in Level II data as well. The identification of WER, BWER, BOW echo and storm top divergence signatures and changes to the maximum reflectivity and the maximum height of the 55DBz reflectivity was governed by the FMH–11.

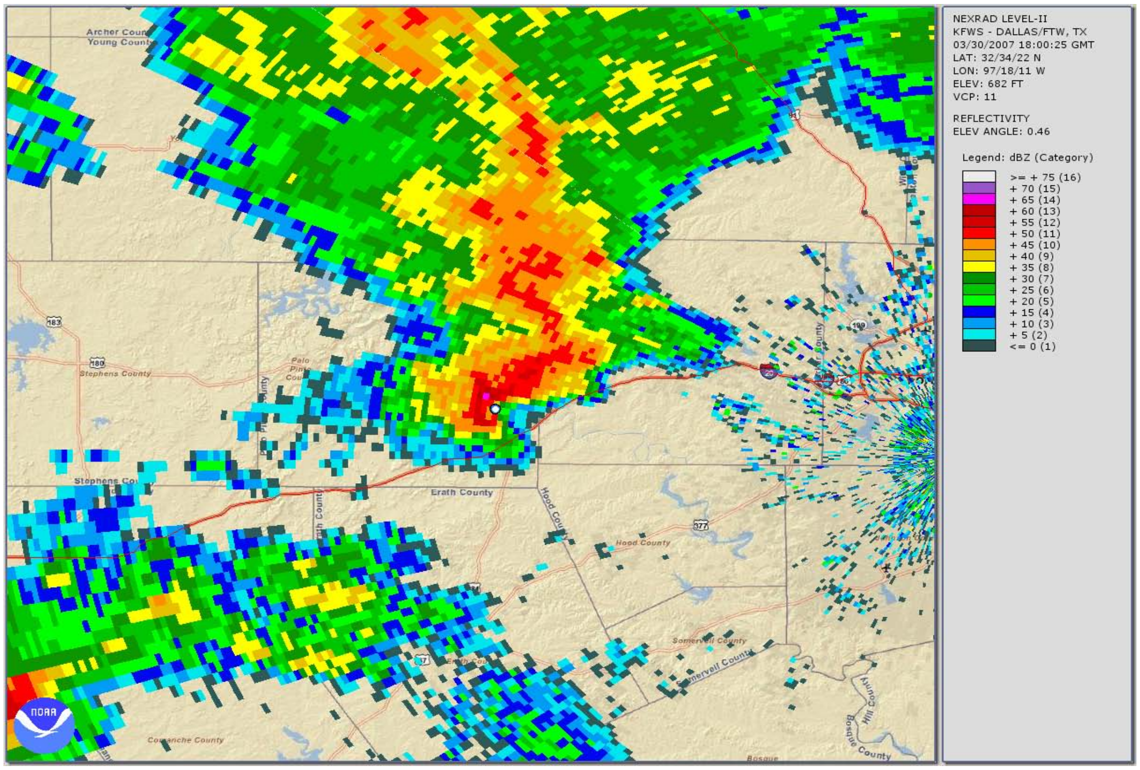

Figure 2. Level II base reflectivity at .49 elevation angle.

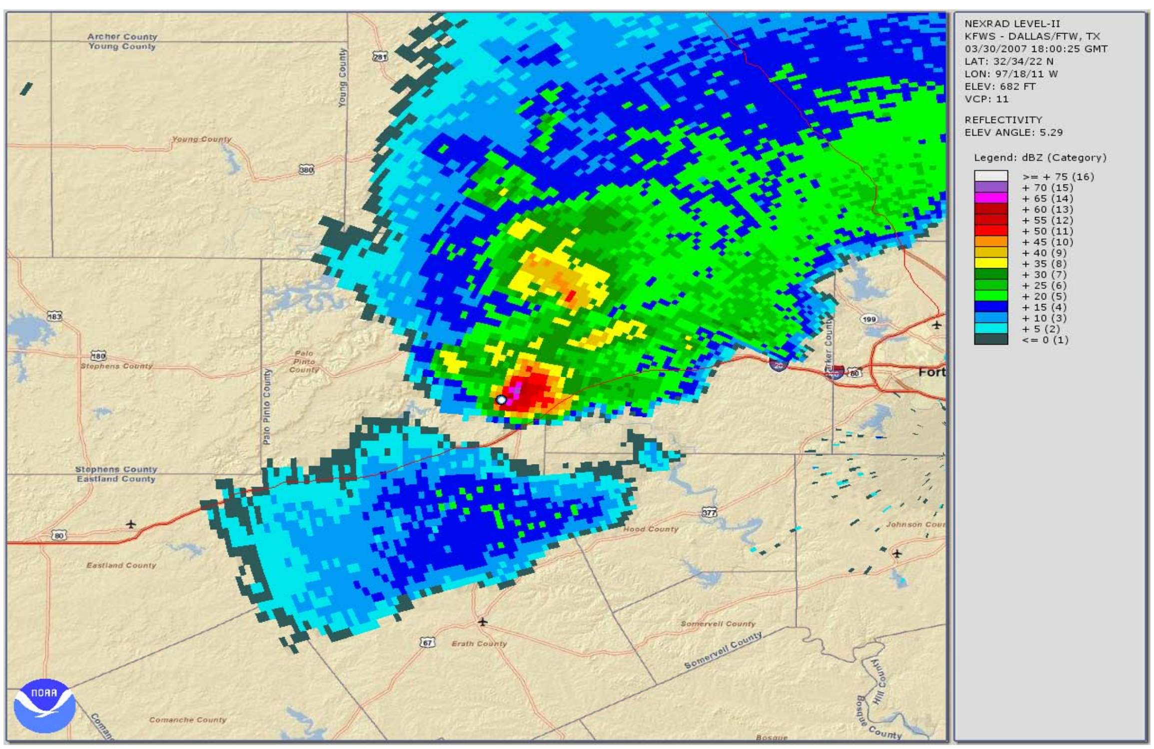

Figure 3. Level II base reflectivity at 5.29 elevation angle (approx 25 Kft)

Figures 2 and 3 illustrate the capabilities of the Toolkit, which allows the user to interrogate storms in accordance with operational standards. In Figure 2, there is a strong thunderstorm viewed at the lowest elevation angel. The toolkit allows the user to mark a point of interest. In Figure 2, an area that is hook shaped and has a high reflectivity gradient is marked. Then the user can move up and down the available levels without affecting the marker. This allows the user to identify WERs and BWERs as well as other aspects of storm structure. The case highlighted in Figures 2 and 3 was a hail event at Mineral Wells, Texas on 30 March 2007. Comparing Figures 2 and 3 indicates there is a strong conical type BWER signature with this storm, in addition to a very high 70 DBz reflectivity (which was present for more than 10kft in the core and was contiguous or not broken into two segments). The Mineral Wells, Texas storm produced two severe hail events (1.75" and then a 0.88" event later).

The main disadvantage to the Weather and Climate Toolkit was the system could not produce a radial cross section to aid in the identification of storm structures and could not produce a four-panel display like the OPUP used in operational settings. This limitation required a careful manual slice-by-slice interrogation and identification method. Although this is much more time consuming, it did reduce the chances for error in identifying structures. Despite the limitations, a slice-by-slice method of interrogation is still close to actual interrogation methods used in operational settings.

2. Lightning Data and Tools

Once the thunderstorms cases were selected based on the occurrence of severe weather and the availability of the radar data, the lightning data was requested from Vaisala Inc., who verified the data for integrity. Vaisala also provided their proprietary LTS2005 software for the interrogation of the lightning data. The LTS2005 software suite allows the user to interrogate not only live data but also archived data in the same way as a live operation.

Figure 4 shows an image from the LTS2005 software for the same event illustrated in Figures 2 and 3. Note, the histogram in the bottom left corner of the image. This histogram shows the flash rate trend over the last six minutes or lightning history.

The histogram is what an operational forecaster would use to help identify a lightning jump. The LTS2005 software will adjust the histogram based on what is occurring in the current field of view. The user can simply change the view if they wanted to look at a particular storm or if they wanted to move to another storm. The histogram will change as will the lightning count read out indicated at the top. In Figure 4, there are two types of lightning indicated, IC lightning and CG lightning. The IC lightning has a habit of obscuring the CG lightning as it looks more like “spaghetti” on the screen while the CG lightning is indicated by either a – or a + to indicate is polarity in addition to the location of the stroke. The screen can be adjusted by the user to increase the lightning history (amount of time included in the window) or decrease it to as little as ten seconds. The time step can be adjusted the same way. The time step and lightning history can be set independently. For this study, the time step was set to one minute with the lightning history displayed was set to six minutes. This configuration was selected for this thesis as it provided a rapid time step update in comparison to the WSR–88D and provided enough of a lightning history of the cell’s lightning activity to help quickly identify lightning jumps. Each storm was zoomed in to limit the amount of lightning flashes from other cells. At each time step, the total lightning, IC, CG- and CG+ flashes were recorded. In the case of a squall line MCS, the individual storms were more easily distinguishable and their individual lightning characteristics were able to be singled out by the LTS2005 software with a minimum of lightning contamination from other cells. This occurred in only two of the 34 thunderstorm cases examined. In cases where individual storms were not easily distinguishable, the case was discarded to prevent lightning contamination.

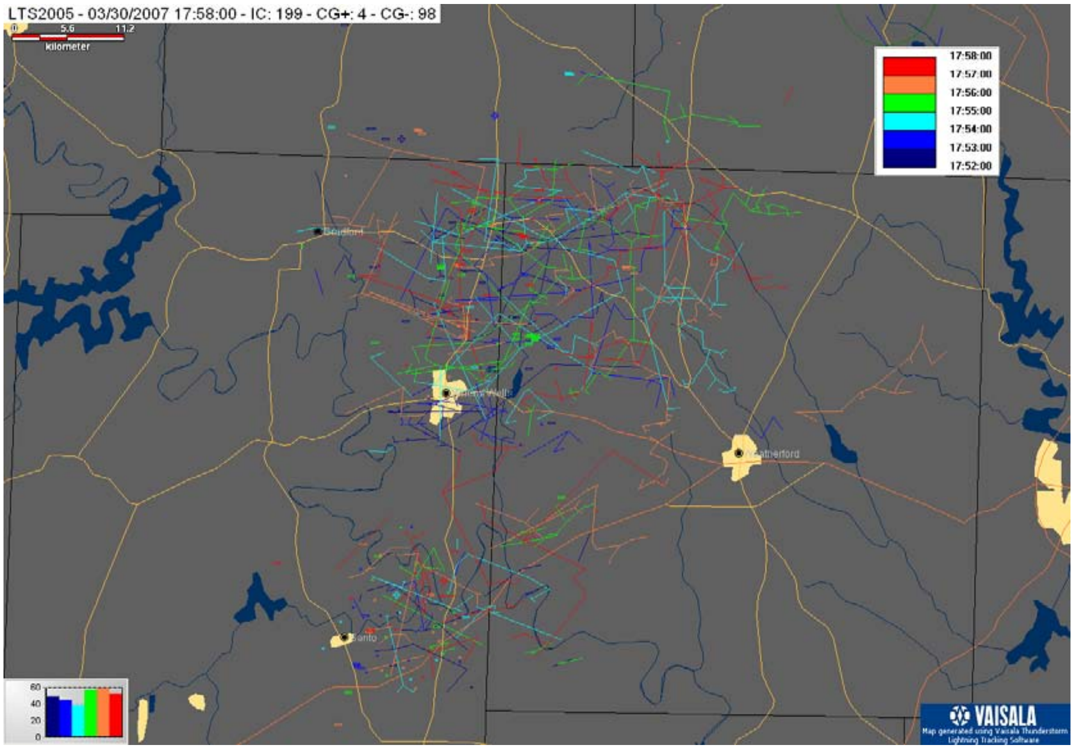

Figure 4. LTS2005 lightning image over Mineral Wells, Texas 30 March 2007

The LTS2005 software also has a few other features including a flash density mode and a cell mode. The density mode shows some promise in identifying lightning holes but this mode was not used as the density mode includes IC lightning from the past ten minutes and cannot be easily adjusted. Since lightning holes are known to be short lived, a 10-minute time window was too long to be considered useful. The cell mode helps the user identify cell boundaries. The cell mode was only used in the initial identification of the cell of interest and when colliding and merging cells had significant IC lightning interaction.

C. DATA COLLECTION AND ANALYSIS

1. Storm Interrogation

For the interrogation phase of the study, the radar and lightning data were interrogated at the same time for each case. At each time step, the lightning counts were entered into a spreadsheet for later analysis, and great care was taken to limit inclusion of lightning flashes from surrounding storms. In cases where cells where merging, lightning

from other storms was unavoidable. The lightning from the colliding cell was then gradually included into the cell of interest. Once vigorous IC lightning interaction between the two cells occurred, the lightning systems of each cell was then considered a single system. The complete inclusion of the lightning activity from the new colliding cell usually occurred before cells can be considered merged on radar. The gradual inclusion of lightning prevented lightning jumps from being introduced artificially into the data. Once there was direct IC lightning interaction between the merging cells, then any lightning jumps could be identified and considered a natural part of the storm's life cycle. It was also during this phase that the lightning jumps were identified. Lightning jumps were classified as an increase of 10 flashes in a one-minute period and the increase must be sustained for three minutes. The 10 flash increase in a minute rule worked well for most cases. In some cases, where overall lightning activity was low (e.g., under 150 flashes in a six– minute period), the storm either did not produce any lightning jumps or the lead time from the jump to the severe weather event was very short. At first, the lack of a lightning jump was thought to be normal for a non–severe storm or low lightning activity severe weather case. When these cases were graphed, it became apparent this was not the case as the slope of the increase in these low lightning activity cases tended to indicate the increase in lightning activity was significant and often stood out more than lightning jumps in high lightning activity cases, as Figures 5 and 6 illustrate.

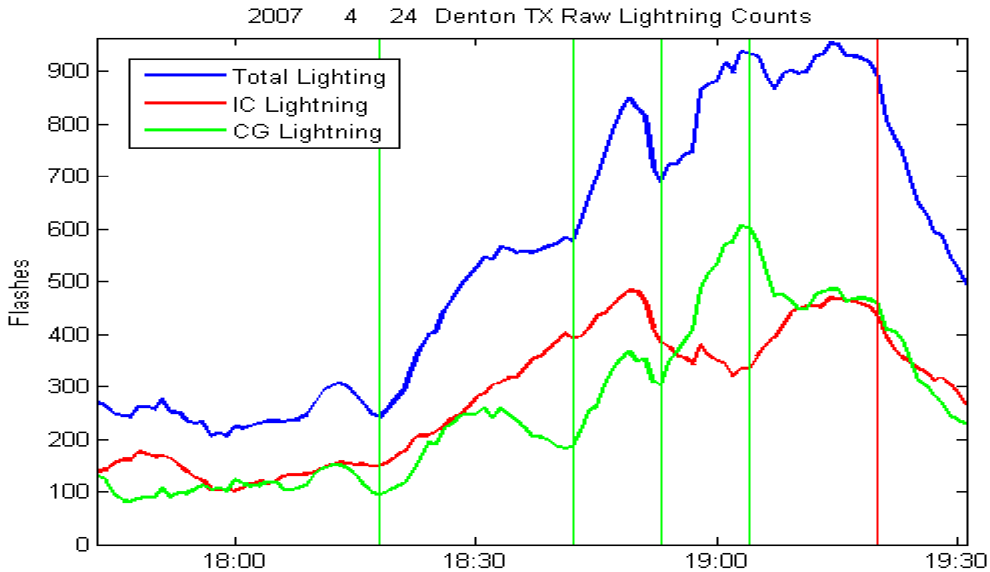

Figure 5. Lightning counts from a high total lightning case with jumps indicated by green vertical lines. Hail by red dashed lines, wind, by red dash/dot lines and tornado by red solid line

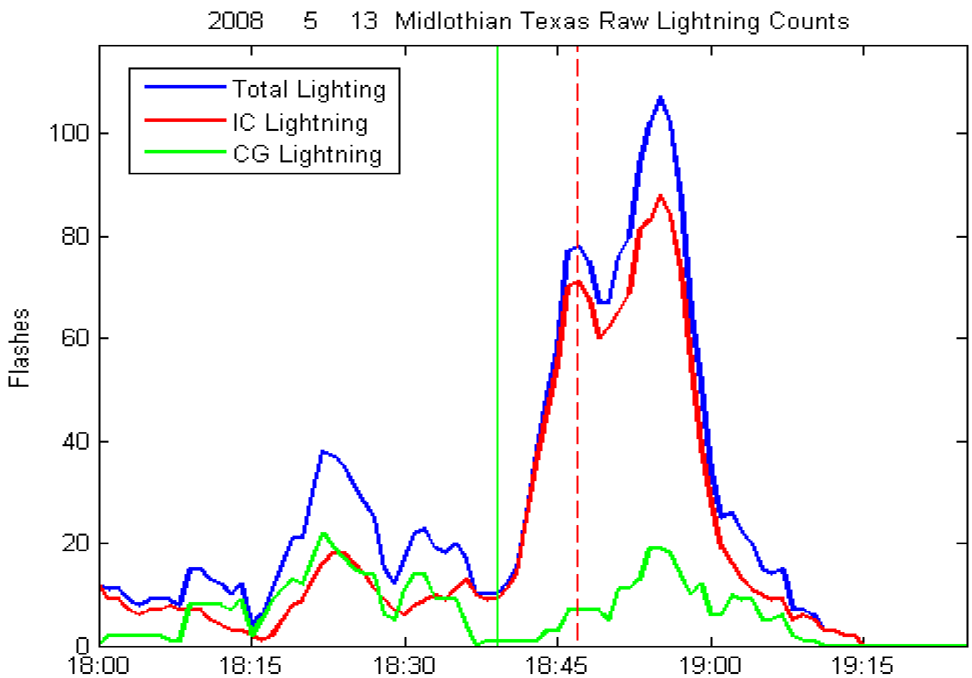

Figure 6. Flash counts from a low total lightning case, Lightning jumps (green vertical), hail (dashed red vertical).

The lightning jump in Figure 6 (a low lightning activity case) clearly stands out more than any of the lightning jumps in Figure 5 (a high lightning activity case). Past studies like the one by Shultz et al. (2009) would have failed to identify a lightning jump or would have been identified with a much shorter lead time to the severe event as the threshold to indicate a lightning jump was set too high. The event in Figure 6 produced 1" hail in Midlothian, Texas and failed to produce more than 150 flashes in any six–minute period. Due to the low lightning activity of the Midlothian, Texas case, the 10 flash increase in a minute requirement was reduced to a five flash increase in a minute for low lightning activity events. The increase in lightning activity still had to be sustained for a minimum of three minutes to be considered a jump. The 5 flash increase in a minute rule produced a jump in not only the case highlighted in Figure 6 but all low lightning activity cases and as a result, the reduced flash rate threshold seemed justified. The reduced threshold for the low lightning activity cases represents an improvement from past studies showing severe weather occurring when no lightning jumps were identified as past studies' higher lightning jump threshold may not have taken into account the individual nature of the lightning in each individual thunderstorm (Shultz et al. 2009; Goodman et al. 2005; Shao et al. 2006).

The radar data was also collected and analyzed in much the same way as the lightning data. A slice-by-slice interrogation of the cell of interest was conducted at each time step. In most cases, a time step was roughly every four and a half to five minutes (VCP 11 and VCP 12 scan setting), in a few cases it was roughly six minutes (VCP 21 scan setting). Information from the cell of interest was collected at each time step to include; maximum reflectivity (DBz), maximum height of the 55 DBz (in feet and had to be contiguous, not broken into segments), VIL, Echo Top, VIL density, Wind Gust Potential (WGP), WER, BWER, MESO, Storm Top Divergence and TVS signatures. The above parameters were entered into a spreadsheet for later analysis. The condition of a contiguous 55DBz column was mandated for this study as it is known that reflectivities greater than 55DBz are the result of the presence of frozen hydrometeors rather than liquid hydrometeors in the form of graupel or hail of any size (FMH–11). The 55 DBz parameter was also chosen based on past studies that indicate storms with DBz >55 had a

much greater chance for high lightning activity and severe weather (Boussantan et al. 2007). Additionally, if there is a contiguous column of 55DBz, it can be reasonably assumed there are higher reflectivities inside the column. Higher reflectivities were found and as some events had a large 75 DBz reflectivities inside the respective 55DBz column. The VIL densities and WGP were recorded for comparison and to test their relationship to lightning jumps, as they are heavily used by the USAF weather forecasters.

2. Other Variables Collected

In addition to the radar and lightning information collected for each case, sounding data was also collected for later comparison to see if there are any currently used sounding derived products that also have a relationship with lightning jumps and the preponderance for high lightning activity storms. The sounding information collected was; Convective Available Potential Energy (CAPE), Severe Weather Threat Index (SWEAT), Showalter Index (SI), Lifted Index (LI), K thunderstorm index (K), Wet Bulb Zero Height (WB0), the -20°C height (M20C) and the Mixed Phase Layer Thickness (MPLT). The MPLT was defined as the thickness between the M20C height and the WB0. The WB0 height was used as it has been empirically shown this level is critical to hail occurrence on the ground (USAF Technical Note 98–02). The sounding time chosen for each thunderstorm case was determined by which sounding time was closest to each thunderstorm's start time. Most thunderstorms in the KTUS area occurred near the 00Z time frame (average four and a half hours on each side of the sounding), and the KDFW thunderstorm a cases had a mixture of 12Z, 18Z and 00Z sounding times. The average difference from the time of the sounding and the start of the thunderstorm event was five hours (either side of the sounding time) for the KDFW cases (several cases had 18Z sounding times available).

3. Data Analysis

Once all the data was collected, the data was entered into spreadsheets and was processed by a MATLAB script to produce graphs and run several parameters including a standardized anomaly of the flash counts, defined by subtracting the mean of the data

sample from the value at a particular time in the data sample, then dividing the result by the standard deviation of the data sample. Each data sample was defined by the length of time the thunderstorm was active (thunderstorm lifecycle). The standardized anomaly has the advantage of setting the mean of the data sample to zero, and places parameters in the same scale making relationships between various parameters easier to identify. The standardized anomaly was used to aid in looking for relationships between the IC and CG flash rates when the IC lightning far exceeded the CG flash rate total. The standardized anomaly had one disadvantage in cases where CG lightning was very low or actually ceased for more than 10 minutes at time, making small increases in CG lightning exaggerated in a standardized anomaly.

In addition to the lightning jumps being identified using the rules explained earlier, each lightning jump was then classified into one of three types; hail type, wind type and mixed. A hail type jump is defined as a lightning jump in which the radar shows a significant increase just before or just after the jump in at least two of the following: max reflectivity, 55DBz height, VIL density, VIL, Echo Top and WGP. Significant increases in the above parameters are generally considered to be hail indications for thunderstorms and are used in the operational setting. Figures 7–9 illustrate the parameters for a hail type jump.

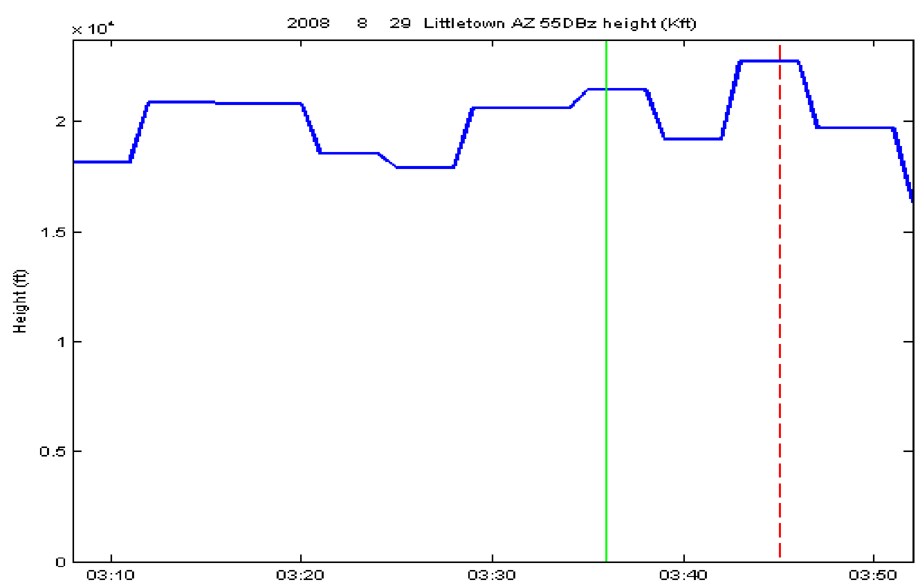

Figure 7. Small increase in the 55DBz height at the time of the jump. 55DBz height (blue trace), lightning jump (green vertical), hail event (dashed red vertical)

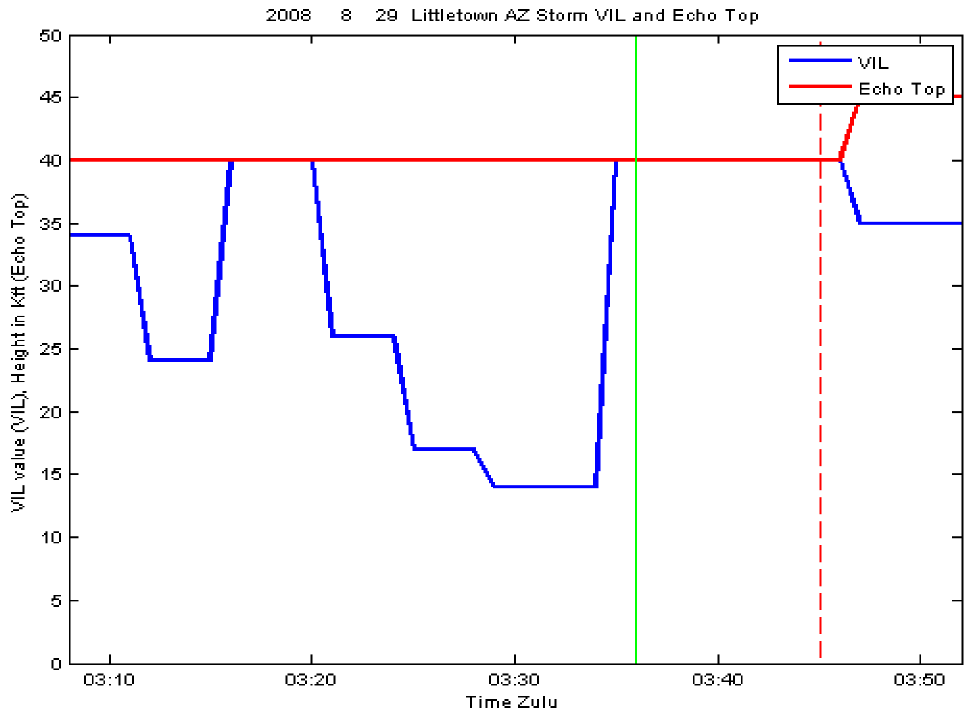

Figure 8. Significant increase in VIL but no change in Echo Top. Lightning jump (green vertical), hail event (dashed red vertical).

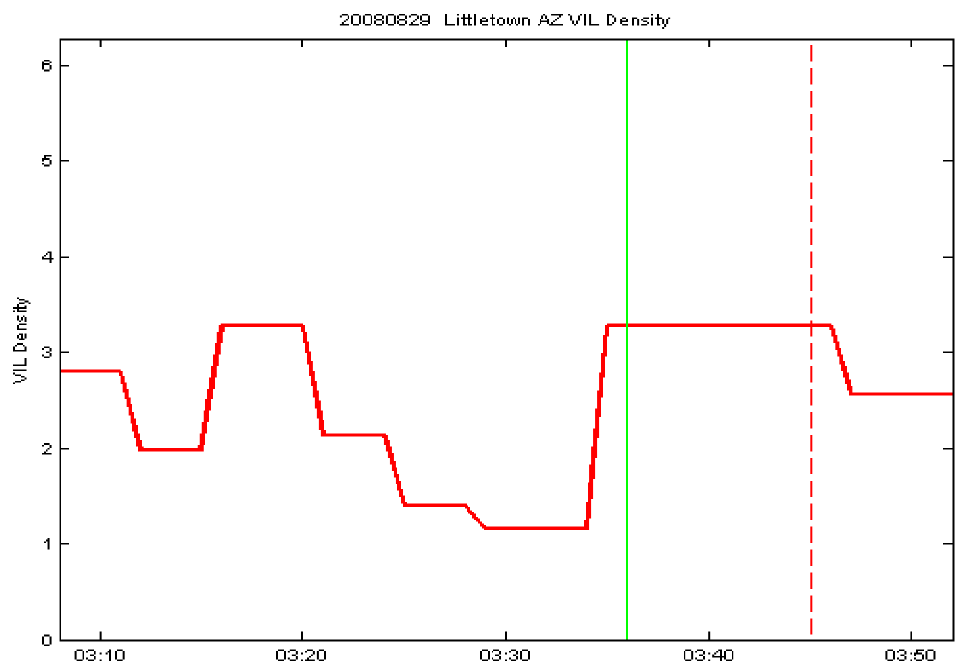

Figure 9. Significant increase in VIL density as well. VIL density (red trace), Lightning Jump (green vertical), hail event (dashed red vertical).

Figures 7–9 indicate two of the stated parameters have significant increases in a short period of time. The 55DBz height in Figure 7 did increase around the same time, but it is not considered significant, but it should be noted that the height of the 55DBz was already over 20Kft at this time putting it at the -20°C level. The increase in VIL and VIL density is a clear indication of the presence of ice in the column. The jumps in the VIL and VIL density are area also considered significant. Current standards in thunderstorm interrogation indicated sudden changes in VIL (FMH–11) and VIL density (Technical Note 98–02) are strong indications of hail.

By contrast, the wind type jump was defined as a significant decrease in at least two of the same parameters mentioned for the hail type of jump. Figures 10–12 illustrate how these parameters look for this classification.

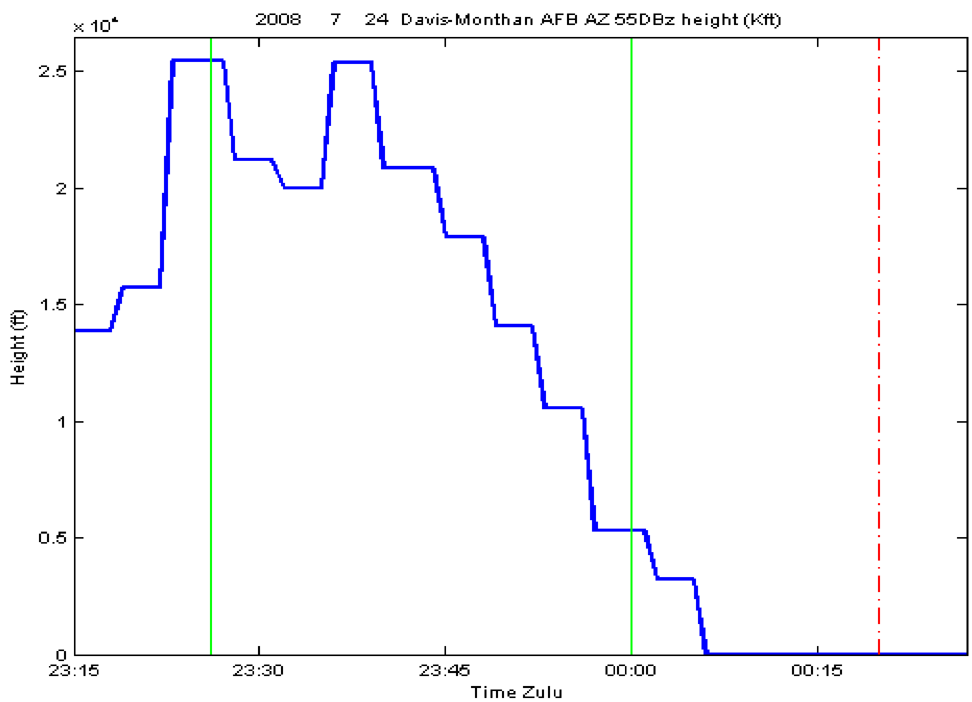

Figure 10. Significant drop in 55DBz height before and during the second jump. 55DBz height (blue trace), lightning jumps (green vertical), severe wind event (dashed–dotted red vertical)

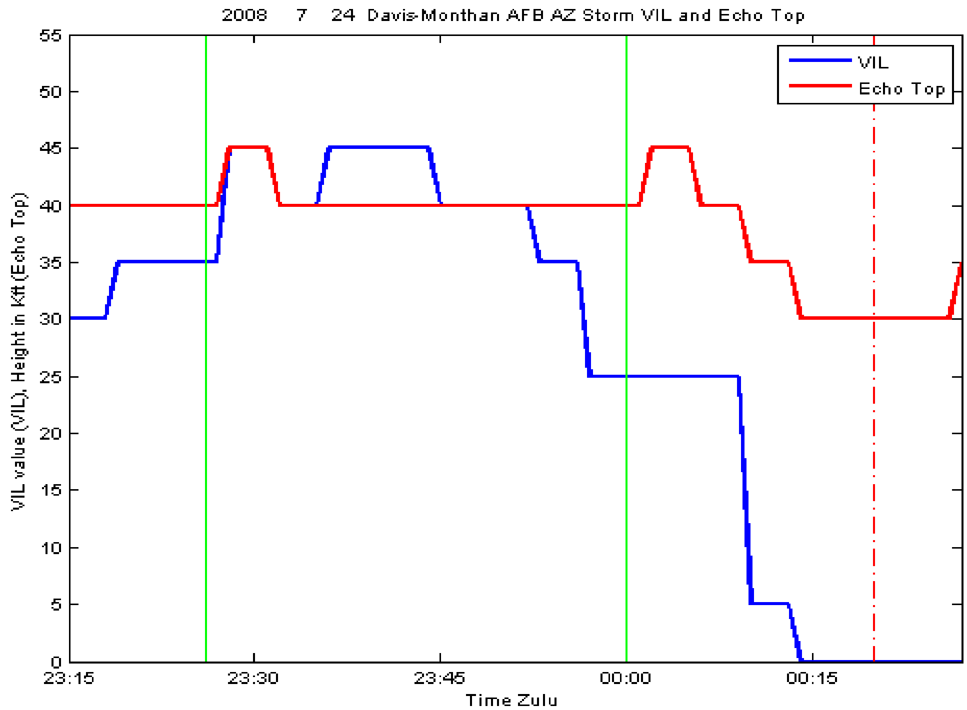

Figure 11. Significant drops in both VIL and Echo Top after second jump, lightning jumps (green vertical), severe wind event (dashed–dotted red vertical)

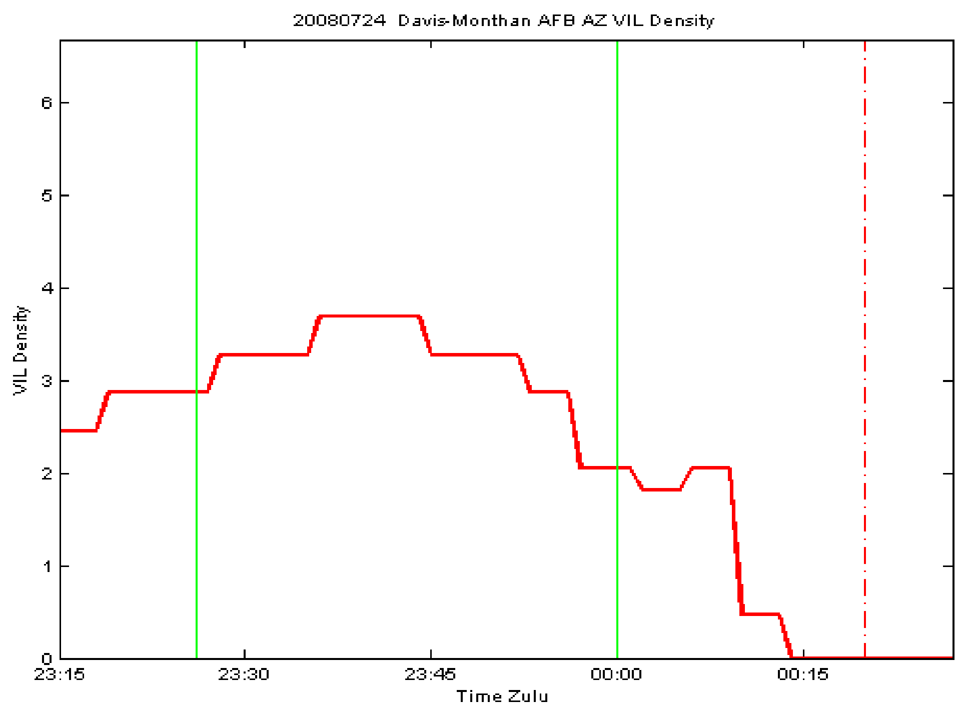

Figure 12. Significant drop in VIL density just after the second lightning jump. VIL density (red trace), lightning jumps (green vertical), severe wind (dashed–dotted red vertical)

Figures 10–12 clearly show a significant drop in the 55DBz height, VIL and VIL density. The FMH–11 and the USAF Technical Note 98–02 both indicate these are signs of a collapsing thunderstorm and severe wind events often follow these changes inside a thunderstorm.

The third type was called mixed, as these were events where either, only one parameter met the criteria, or there were conflicting readings within the storm (e.g., 55DBz height increased but VIL decreased).

The lightning jump data was also compared to the start time of several radar derived storm structures which included; WER, BWER, MESO, TVS and Storm Top Divergence. These structures and signatures were chosen, as they are some of the primary parameters used to interrogate thunderstorms to gauge their severity. This thesis is intended to find what relationship (if any) exists between these structures and the occurrence of the lightning jumps.

The levels of significance for the radar derived parameters depended on the variable. For the 55 DBz parameter, a change of 1000ft in a single volume scan was considered significant. For VIL, a change of 10 in a single volume scan was considered significant. For VIL density, a change of .5 in a single volume scan was considered significant. For Echo Top, a change of 10,000 ft in a single volume scan was considered significant. For Wind Gust potential, a change of 15kts in a single volume scan was considered significant.

All of above parameters were collected and then each thunderstorm case was categorized in the following manner: severe cases, non–severe, high lightning activity storms and low lightning activity. High lightning activity storms included both severe and non–severe cases as did low lightning activity cases and was solely based on lightning activity of the individual storm. The determination of severe and non–severe cases depended solely on the reports of severe weather on the ground.

The lightning jumps were categorized in each thunderstorm case based on what IC and CG lightning behavior at the time of the jump with respect to each other. They were separated into the following groups: IC increasing while CG decreasing (or steady),

both IC and CG increasing, or IC decreasing (or steady) while CG increasing. The sounding derived data was also compiled for the severe and non–severe cases and high and low lightning activity cases. The IC/CG behavior and sounding data was compared to the three different types of lightning jumps (hail type, wind type and mixed as described before).

IV. RESULTS

A. LIGHTNING JUMP CHARACTERISTICS

As stated earlier, all the lightning jumps from the cases studied, were classified into to three groups, hail type, wind type and mixed type. The hail, wind and mixed types were determined by the characteristics and structures found in the radar data at that time. A total of 73 lightning jumps were identified in 34 thunderstorm cases, where 34 lightning jumps were classified as hail type, 20 were classified at wind type and 19 were classified as mixed.

1. Hail Type Jumps

For hail type jumps that are classified based on increases in the 55 DBz heights, VIL and VIL density, one would expect these occurrences would be more likely to produce hail than any other form of severe weather. Of the 34 hail type jumps, only 18 hail type jumps directly preceded a severe weather report. The distinction is important as not all lightning jumps, whether they are hail, wind or mixed type, will always precede a severe weather event. In many cases, another lightning jump followed a lightning jump. As a result, there was a much higher number of lightning jumps than there were severe weather events. The average lead time for a hail type lightning jump directly preceding a severe weather event was 14 minutes. Of the 18 severe weather reports directly following a hail type jump, 14 produced hail, three produced winds and one tornado event. At the time of each lightning jump, the behavior of the IC and CG lightning activity was analyzed to find any particular pattern that could be of use to the operational forecaster. To find a pattern, the individual lightning jumps were broken down in to the two different categories, IC increasing while CG decreasing (or steady) and IC increasing while CG increasing. For the 34 hail type jumps, 25 jumps showed IC increasing while CG was decreasing (or steady). In some cases, the CG would cease entirely. The cessation of CG lightning activity was also a trait noticed among tornadic storms, especially storms that produced violent tornadoes of the F4 to F5 category (Perez et al. 1997; Steiger et al. 2007a). The relationship of the lightning jumps and tornado producing storms will be discussed later in this section.

Figure 13 is from Lakeside, Texas illustrates the relationship between IC and CG lightning during a hail type jump. The second lightning jump in Figure 13 shows IC lightning increasing significantly breaking the 10 flash increase threshold in a minute while the increase in CG lightning suddenly comes to a stop and becomes steady. The first lightning jumps in Figure 13 was triggered by an increase in CG lightning and the first lightning jump was classified as a wind type (discussed later), the second jump was triggered by an IC lightning increase and this lightning jump was classified a hail type jump. Not all lightning jumps classified as hail type directly precede a hail event, as three did directly precede a severe wind event. Two of the three hail type jumps identified that directly preceded severe wind events also produced hail. The time difference between the wind and hail was less than six minutes. Figure 14 illustrates an event from Oro Valley, Arizona where severe wind and hail occurred in very close time proximity. The last lightning jump, classified as a hail type jump, occurs 17 minutes prior the wind event, then five minutes later, the hail is reported. The wind and hail events occur so close together, they could be considered a single severe event. For this thesis, they were separated as they produced two different types of severe weather and to illustrate that a hail type jump is not exclusive to hail production. The large amount of hail falling out of a thunderstorm can produce severe winds by merely pushing and/or pulling the air from within the cloud down to the surface with the hail.

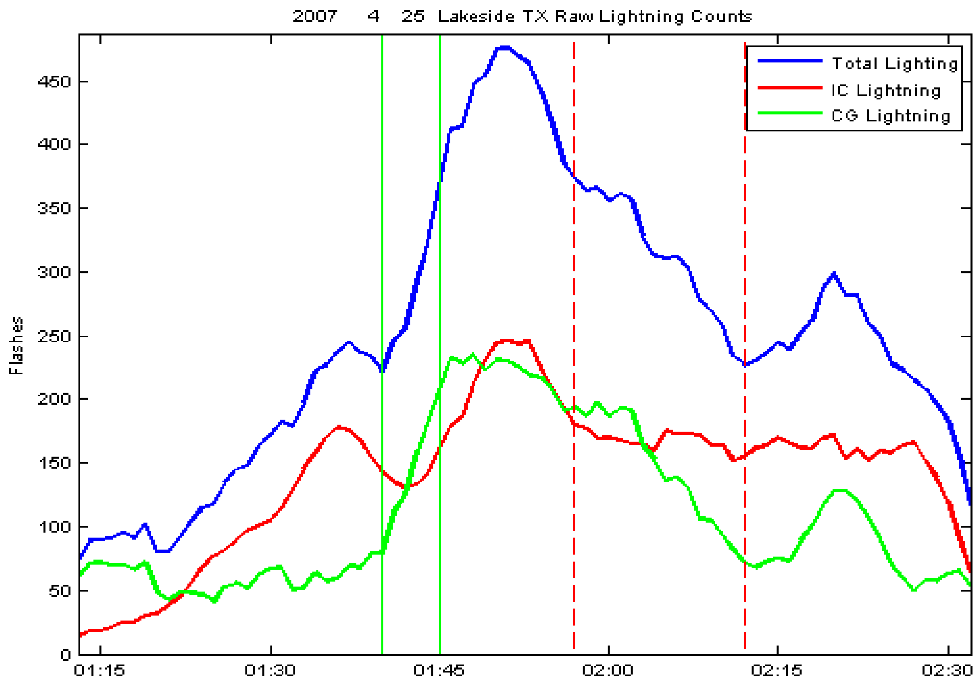

Figure 13. IC lightning is increasing while CG is decreasing prior to hail event. Lightning jumps (green vertical), hail event (dashed red vertical)

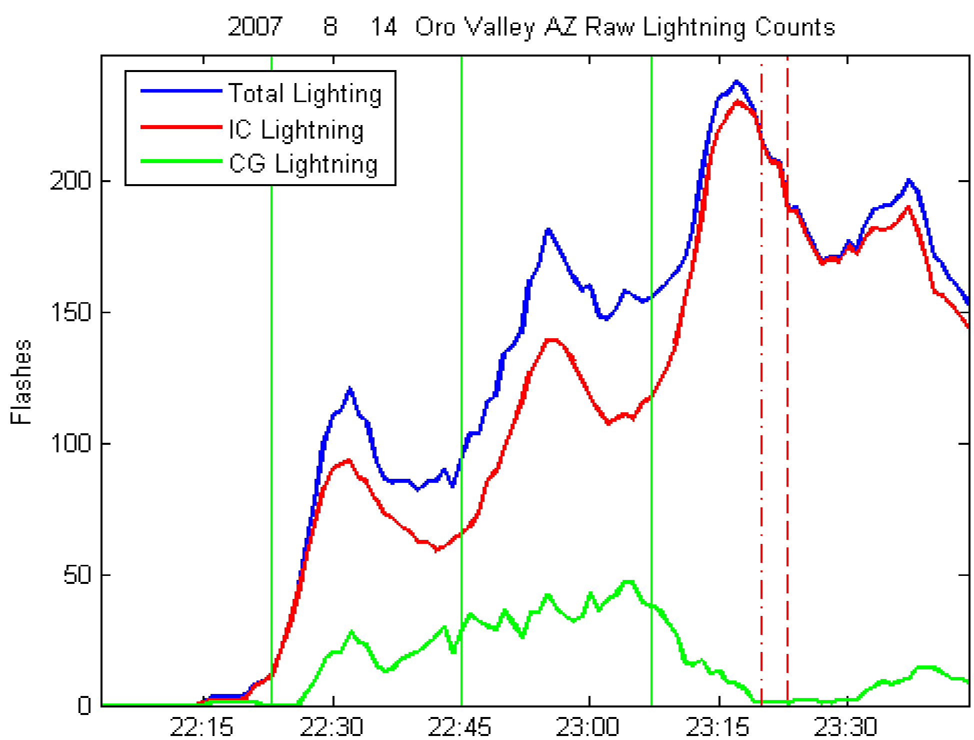

Figure 14. Last lightning jump (hail type) shows IC increasing and CG decreasing. Lightning Jumps (vertical green), hail (dashed red vertical)

Figure 14 also illustrates that there can be multiple lightning jumps in a thunderstorm and, in this case, only one of them was followed by a severe weather event. Therefore, if lightning jumps are the sole source for predicting severe weather, there is a high false alarm rate. Figures 13 and 14 also indicate a pattern of behavior between the IC and CG lightning with a hail type where the IC lightning will be the primary factor showing an increase while the CG lightning activity will either remain steady or decrease. This characteristic is more readily seen when the IC and CG flash counts are plotted against each other in a standardized anomaly chart. Figure 15 shows the nature of IC and CG relationship during a hail type jump at Littletown, Arizona. Figure 15 shows the IC and CG standardized anomaly lightning plots begin to diverge at the time of a hail type lightning jump and prior to the hail event. The divergence was visible in all lightning jump events that displayed this IC and CG behavior on a standardized anomaly plot, including events where the changes in actual lightning counts were more subtle and difficult to see.

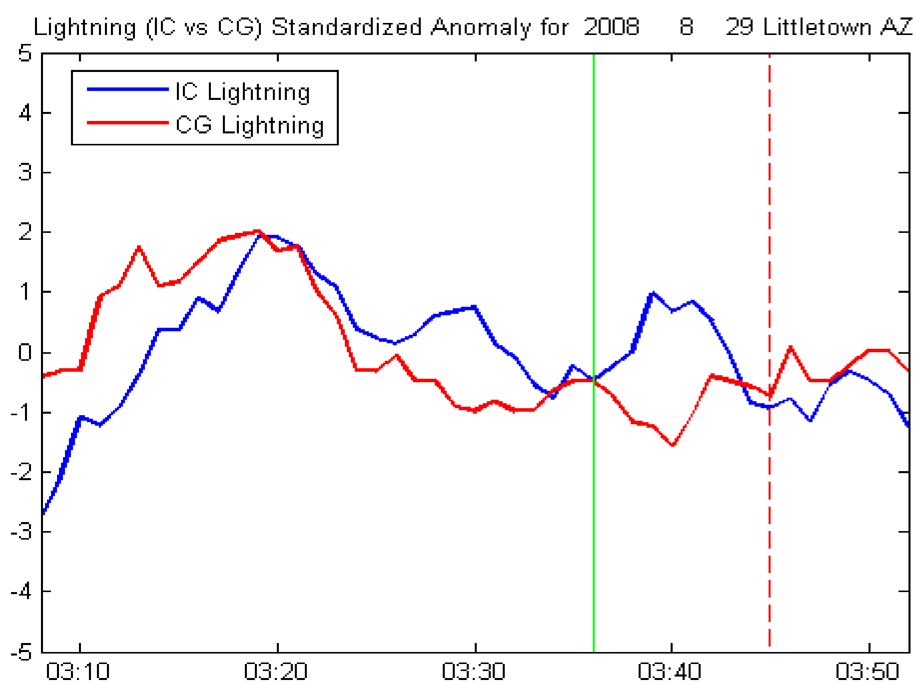

Figure 15. IC and CG are divergent at the hail type jump time, lightning jump (green vertical), hail event (dashed red vertical)

The behavior noted in Figures 13–15 was the dominate pattern noted for the hail type jumps. It occurred in 25 of the 34 hail type lightning jumps yielding a ratio of 2.7:1. Nearly a 3:1 preference for the hail type jump to display IC increasing while CG either remained steady or decreased. For the 18 hail type jumps that directly preceded a severe weather, 14 directly preceded hail yielding a 3.5:1 ratio of hail occurring over wind or tornadic activity occurring. The preference of hail occurring should be expected as the hail type jump is directly related to changes in the radar derived parameters that have been proven to be likely indicators of hail in the storm.

Not all hail type jumps will produce hail. Figure 14 shows a wind event occurring at nearly the same time as the corresponding hail event. In some cases, only severe wind was produced. In Figure 16, a hail type jump occurred 11 minutes prior to a severe wind event. It should be noted the hail type jump does not exhibit the same IC/CG characteristics of the other hail type jumps. In figure 16, the IC and CG are both increasing instead of only the IC increasing. The case in Figure 16 was the one of two hail type jumps that only produced wind. Additionally, there were eight other hail type jumps that also exhibited this same IC and CG behavior, but only three of them directly preceded a verified hail event. So, this thesis cannot say that IC increasing and CG decreasing (or steady) is solely a characteristic of the hail type jump, only that is tends to strongly prefer hail over other types of severe weather.

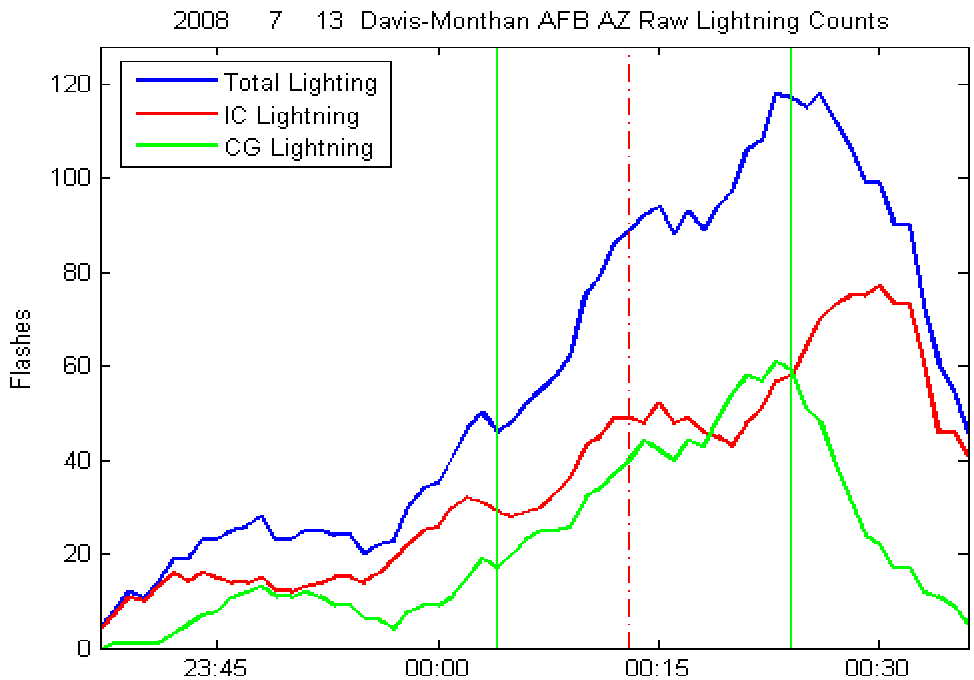

Figure 16. IC and CG are both increasing after this hail type of jump (1st jump). Lightning jumps (green vertical), severe winds (dashed–dot red vertical)

2. Wind Type Jumps

The wind type jumps were also classified in accordance with changes in the radar signatures that have been shown to produce severe winds, mostly in the form of a collapsing thunderstorm (FMH–11). Sudden and significant decreases in 55 DBz height, VIL and VIL density were the primary feature changes used to classify the wind type lightning jump. Wind type lightning jumps were also categorized depending on the characteristics between IC and CG lightning. For wind type jumps, they were categorized as IC increasing while CG decreasing (or steady), CG increasing while IC is increasing and CG increasing while IC is decreasing (or steady). There were 20 wind type lightning jumps. Of the 20 wind type jumps, only two jumps showed IC increasing while CG was decreasing, 12 jumps had both IC and CG increasing while 6 jumps had CG increasing while IC was decreasing (or steady). The results indicate that CG rarely decreases with wind type jumps and IC either increases along with the CG or actually remains steady. This makes a ratio of 18:1 against CG falling during a wind type

lightning jump. Of the 20 wind type jumps identified, there were 12 of the wind type jumps where severe weather events followed them. Two of them were hail events, seven were wind events and three tornado events. The results seem to suggest the wind type jumps tend to produce wind events.

Figure 17 shows the predominate relationship between IC and CG lightning during a wind type jump. In Figure 17, the IC lightning activity actually decreases and is rapidly overtaken by the CG lightning activity. The IC lightning does recover with an increase of its own but it fails to overtake the CG lightning activity. Figure 18 shows the indicated wind type lightning jump relationship further when the IC and CG lightning activity is plotted against each other in a standardized anomaly chart.

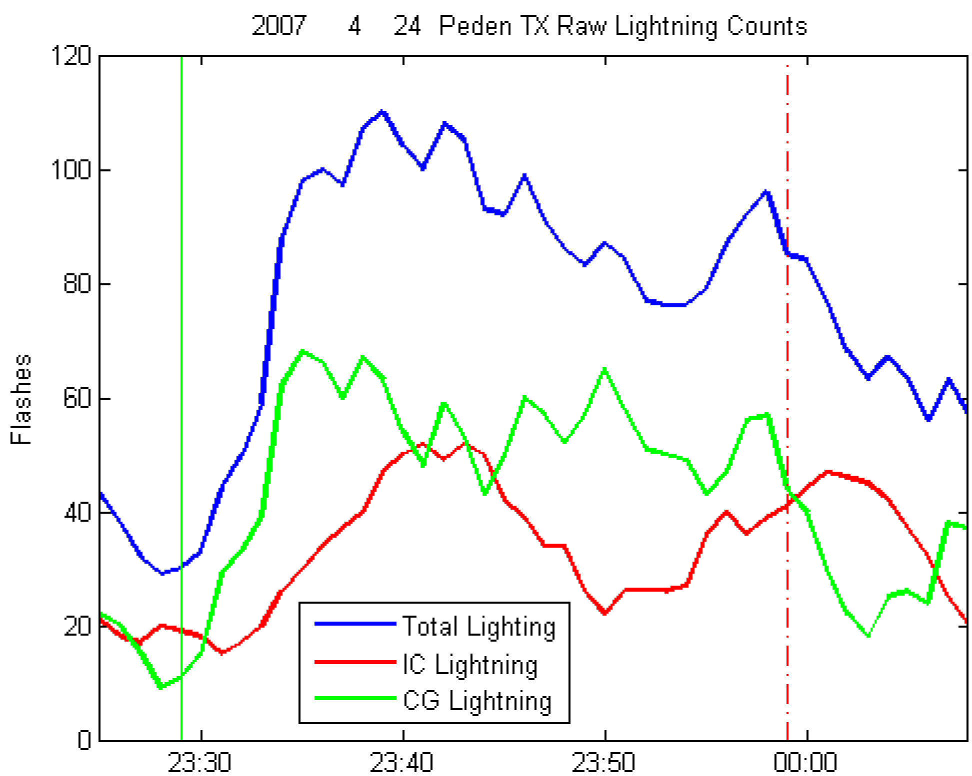

Figure 17. Wind type jump CG increases while IC decreases. Lightning jumps (green vertical), severe wind (dashed–dot red vertical),

Figure 18 shows the IC and CG lightning plots crossing each other with the CG increasing. Again, you can see the IC begin to increase a short time later but its rate of

increase s still not as significant (fails to achieve an increase of 10 flashes in a minute) as the CG activity and the IC activity only overtakes the CG lightning activity after the rate of the CG lightning increase stops. IC lightning activity again falls below the CG for a short time later but there is not a jump in CG activity at that time as the jagged nature of the CG plot indicates the increases are not sustained.

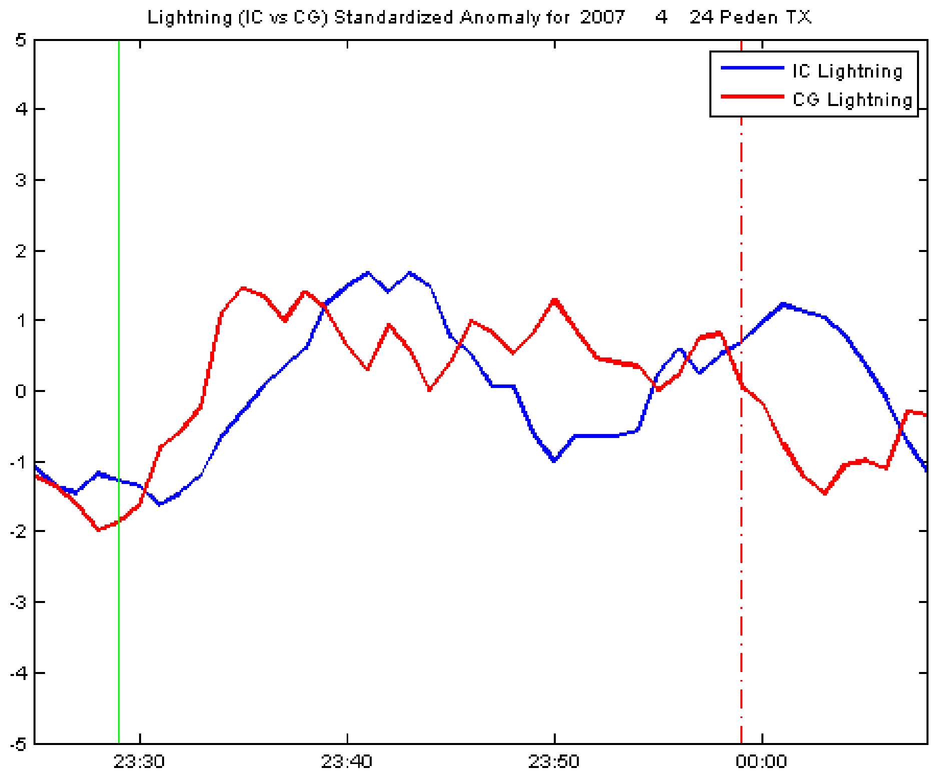

Figure 18. Standardized anomaly chart if IC and CG plotted against each other. Lightning jumps (green vertical), severe wind (dashed–dot red vertical)

Most wind type jumps displayed the IC and CG lightning activity increasing at the same time. Some of the time, the rate of increase appeared to be same but in many cases the rate of increase of CG tended to increase faster than the IC, as in Figure 17 and 18. Figure 19 shows the same CG increasing faster than IC relationship, but it is a little harder to see. In Figure 19 the wind type lightning jump, the IC and CG lightning are increasing at the same time and appear to be increasing at the same rate. It should be noted in Figure 19, the CG lightning increase is sustained for a longer period of time. CG increasing for a longer period of time than an IC, appeared to be common trait in the

wind type jumps. Only five of the 20 wind type jumps did not display a sustained increase in CG lightning activity that was longer than the sustained increase in IC lightning activity. Figure 20 shows the standardized anomaly for the thunderstorm case in Figure 19.

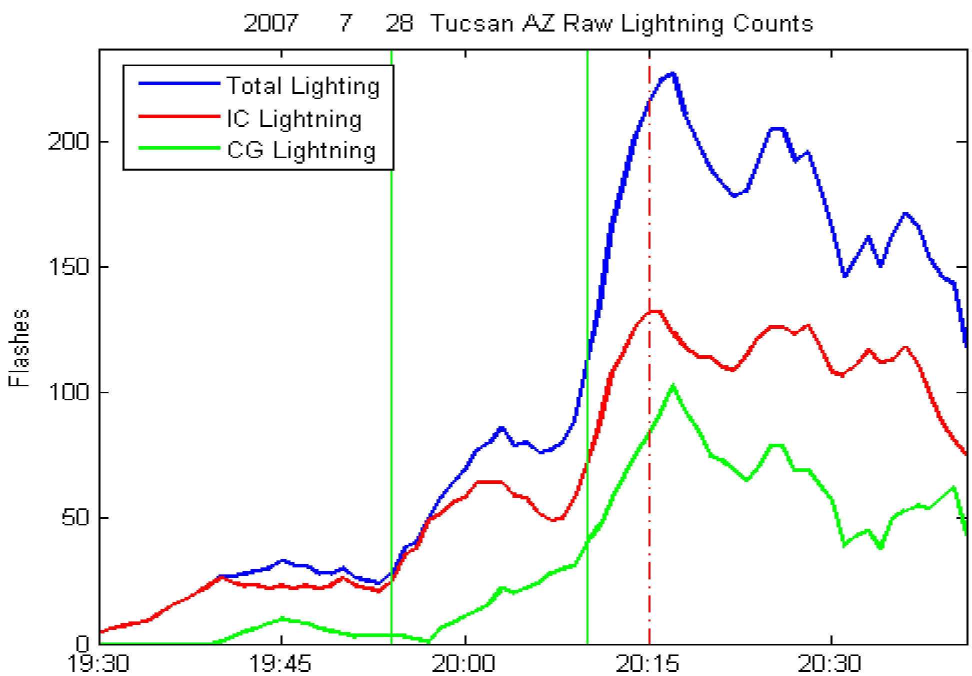

Figure 19. Wind type with CG and IC increasing at the same time. Lightning jumps (green vertical) severe wind (dashed–dot red vertical)

In Figure 20, it is clear the IC and CG lightning parts of second jump have a similar rate of increase, but the CG portion is sustained for a longer period of time and even continues past the severe weather event which was not a common characteristic of any of the lightning jumps. In most cases, the lightning activity would decrease or at least level off just before a severe weather event.

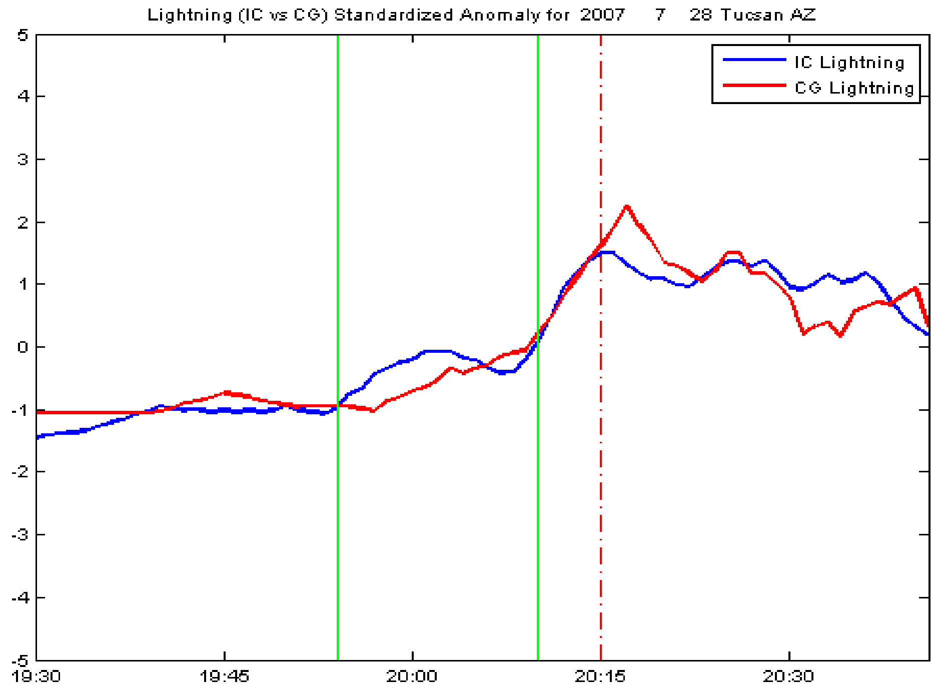

Figure 20. Standardized Anomaly with IC and CG plotted. Lightning jumps (green vertical), severe wind (dashed–dotted red vertical).

The results from the wind type jumps, like the hail type jumps, shows a correlation between the changing storm structure as seen on radar and the characteristics of the lightning. The behavior or the IC and CG lightning with the wind type jumps is expected as the wind type jumps were identified by significant decreases in 55DBz heights, VIL or VIL density, which are strong indications of a collapsing thunderstorm that are known to produce severe wind events (FMH–11, Technical Note 98–02). For the wind type jumps, 18 of the 20 had CG lightning increasing and CG lightning tended to be the primary source of the lightning jump. In 12 of the 18, IC and CG would increase together while 6 of the 18 had IC decreasing or steady. In contrast, the hail type lightning jumps tended have an increase in IC lightning while CG lightning tends to stay the same or decrease.

3. Mixed Type Lightning Jumps

The remaining lightning jumps could not be classified as either hail or wind type due to the fact the radar either showed no significant changes in the key parameters or

showed conflicting changes in the key parameters. There were 19 lightning jumps of the 73 total lightning jumps classified as mixed. The mixed type lightning jumps were categorized in the same way as the hail and wind type. Of the 19 lightning jumps classified as mixed, eight displayed IC increasing while CG was decreasing (or steady), seven displayed both IC and CG increasing and four displayed IC decreasing (or steady) while CG was increasing. The wide dispersion of characteristics indicates there was no predominate IC and CG behavior like the hail and wind type jumps displayed. Nine of the lightning jumps directly preceded a reported severe weather event. Five of the events were severe wind, three were hail and one was a tornado. The wide spread of severe weather activity following a lightning jump classified as mixed also indicates there is no practical pattern to this type of jump.

Figure 21 illustrates IC and CG lightning behavior typical of a hail type lightning jump. The jump in Figure 21 was classified as a mixed type as there was a significant increase in Echo Top causing a significant decrease in VIL density. The 55DBz height only showed a small change and was not considered significant and the increase in VIL was not large enough to be considered significant either. The jump in Figure 21 occurred 15 minutes prior to a 70Kt wind event, which illustrates severe weather events do occur in these cases. The radar also indicated a BWER and MESO signature 15 minutes prior to the severe wind event. The pattern of the lightning traces in Figure 21 is even more like a hail type jump when it is plotted in a standardized anomaly chart. Figure 22 shows the CG lightning plot practically nose diving below the IC lightning plot. Again, from what was shown in the hail jump type section, the divergence behavior indicates a hail possibility but again, only wind occurred from this event.

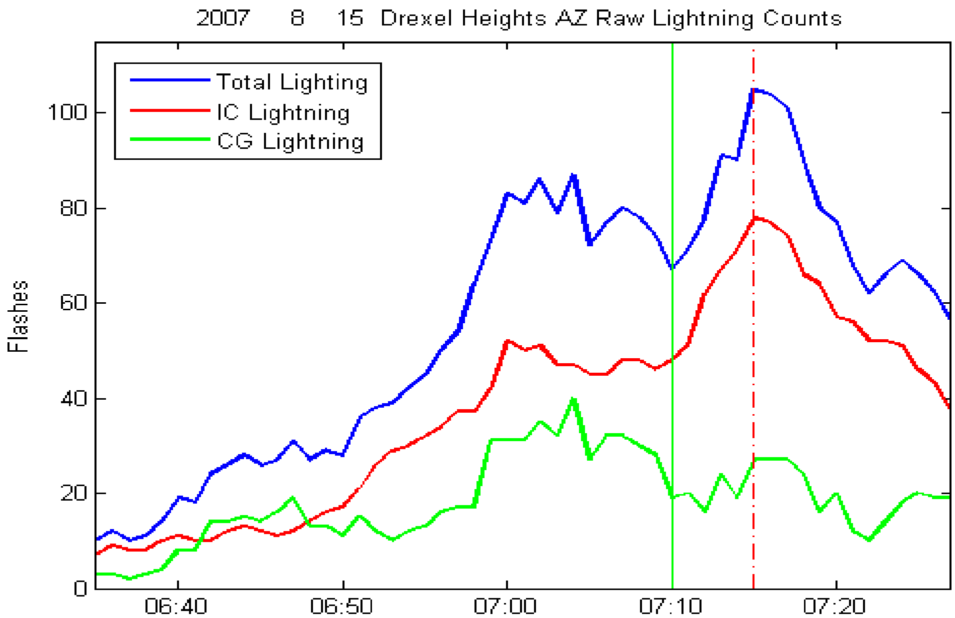

Figure 21. Other type lightning jump showing IC increasing with CG decreasing. Lightning jump (green vertical), severe wind (dashed–dot red vertical)

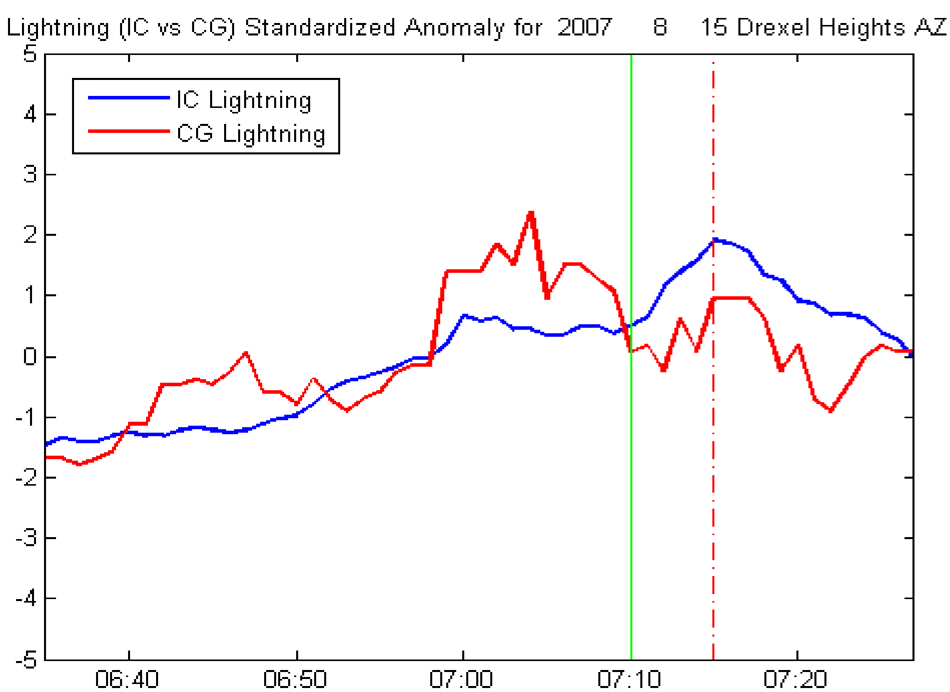

Figure 22. Standardized Anomaly of IC and CG lightning. Lightning jump (green vertical), severe wind (dash–dotted red vertical).

Not all mixed type lightning jumps had severe weather follow them and still display the same IC/CG lightning characteristics as in Figures 21 and 22. Some of the jumps displayed characteristics similar to that of the hail type (IC increasing while CG decreasing or stead) and wind type (IC and CG increasing or IC steady or decreasing). In Figures 23 and 24, two different mixed type lightning jumps occur, one precedes a hail event and the other precedes a wind event. The first lightning jump in Figure 23 shows the IC lightning increasing while the CG lightning remains steady which is a behavior of a hail type jump. The second jump has IC lightning slowing and leveling off to become steady while the CG lightning increases rapidly. The behavior of the second jump is a characteristic of the wind type jump and of the severe wind events in general, as explained in the wind type jump section.

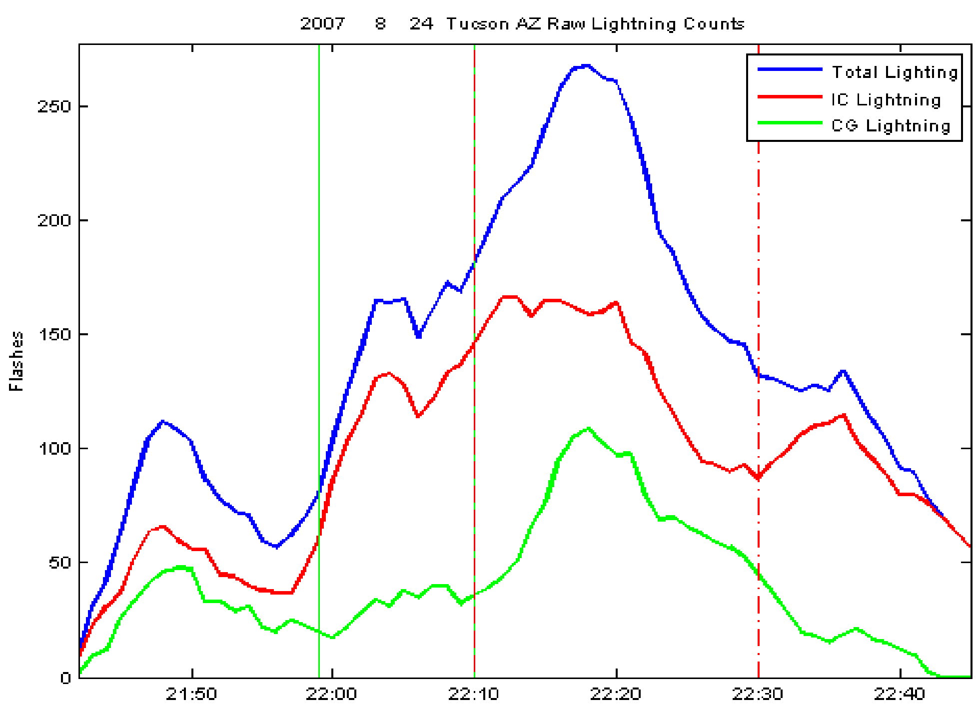

Figure 23. Two mixed type lightning jumps displaying hail and wind type IC/CG relationships. Lightning jumps (green vertical), hail event (dashed red vertical), severe wind event (dashed–dotted red vertical)

Figure 24 shows the same thunderstorm event as Figure 23 but plotted in a standardized anomaly chart to reinforce the findings in Figure 23. Figure 24 shows the

first jump with an inverse relationship between the IC and CG lightning counts, which is a behavior that is in line with the general pattern explained in the hail type jump section. The second jump, which directly precedes the wind event, clearly displays a much stronger CG increase than the IC. In fact, the IC shows signs of decreasing but mainly remaining steady a behavior that is in line with the findings explained in the wind type lightning jump section.

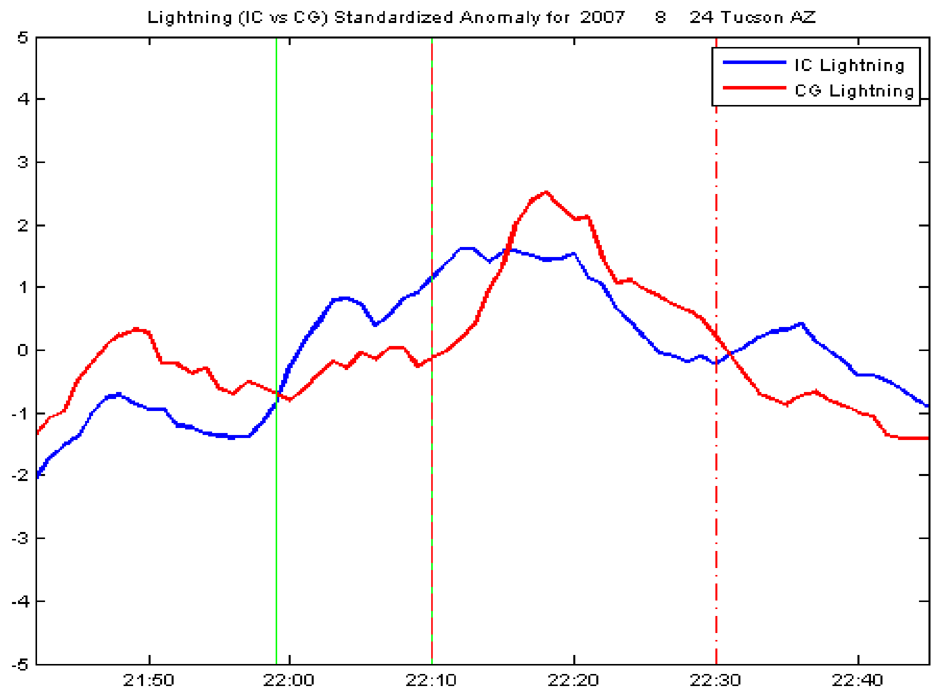

Figure 24. Standardized Anomaly showing two "other" classified jumps preceding severe events. Lightning jumps (green vertical), hail, (dashed red vertical), severe wind (dashed–dotted red vertical).

The behavior in Figure 24 seems to indicate the IC/CG behavior for mixed type lightning jumps tend to be same as the trends in the hail type (directly preceding a hail event) and wind type (directly preceding a severe wind event) lightning jump sections, but it cannot be taken as an absolute. There is too much of a spread in the hail, wind and tornado events that directly follow mixed type jumps to make that assumption. The wide spread in the results of the mixed type jumps indicates there are more, subtle changes occurring in the thunderstorm that this study was not able to readily identify. The smaller

changes in the thunderstorm structure may have an effect on the storms lightning behavior and structure that lead up to the occurrence of severe weather.

4. Severe Case

In this part of the analysis, only the storms that produced severe weather were examined in an attempt to see if the occurrence of severe weather has an effect on the behavior of the IC and CG lightning activity, and if that behavior is different from the trends discovered in the previous sections. Of the 34 thunderstorm cases, there were 40 severe weather events. In several of the cases, there were multiple severe weather events from one storm and at times, multiple severe weather events following a single jump. As a result, the trends became more difficult to see. There were 17 hail events, 18 wind events and five tornado events. Of the hail events, 11 of the 17 displayed the same IC/CG relationship common among the lightning jumps classified as hail type. The preponderance of the IC/CG behavior to mirror the general results from the hail type section indicates some agreement with the findings of the hail type. For the severe wind cases, 15 of the 18 events showed a similar IC/CG lightning relationship of IC and CG increasing or IC decreasing (or steady) while CG was increasing. Only three of the events out of the 18 did not display this characteristic. The result yields a 5:1 ratio for the lightning for severe wind events to display the common characteristics of the wind type lightning jump.

The tornado events were too few in number to draw any conclusions on the characteristics of IC and CG lightning. There were five tornado events produced by four different storms. The lightning counts from all four storms reached the threshold of at least 150 flashes in one six-minute period to be considered a high lightning activity storm. Two of the storms had some of the higher lightning counts recorded in this study with counts reaching 500–900 flashes in one six minute period. The high IC lightning activity noted in these storms is in line with previous studies indicating tornado producing storms to be high IC producers (Pierce 1977; Williams et al. 1999; Goodman et al. 2005). The other two were much lower and fell in the range of 150–180 flashes in a six minute period. All four storms had multiple lightning jumps prior to the tornado

events while one storm had four jumps prior to the tornado event. Again, considering the very small sample of tornado events captured in this thesis, no conclusions or assumptions can be made from this data set on the relationship of tornados and lightning jumps.

5. Non–Severe Cases

In this section, like the severe cases, the non–severe cases were examined solely on their lack of reported severe weather to see if these storms showed a different trend the trends found in the hail type (lightning jumps), wind type (lightning jumps) and mixed type (lightning jumps). The non–severe cases were selected from the same data set and often occurred the same day as the severe case but were just weaker storms that failed to produce any reported severe weather. Selecting non-severe storms from the same day as the severe cases helped to insure the atmospheric dynamics would be the same as the severe cases and highlight the difference in the storms and lightning characteristics. There were nine non–severe cases examined in this thesis. More non–severe cases would have been ideal, but many potential cases had to be discarded as the prospective storms were either too far away from the lightning detection system or could not be distinguished between the surrounding cells well enough to prevent contaminating the sample.

The non–severe cases displayed much of the same characteristics as the severe cases. An expected artifact of the non–severe cases is many of them were classified at low lightning activity storms. Five of the nine non–severe storms fell into this category. All the non–severe cases exhibited lightning jumps for a total of 16 lightning jumps. Nine of the lightning jumps were classified as hail type and four wind type and three mixed type.

Taking a closer look at the hail type jumps, six of the nine hail type jumps displayed the same increase in IC and decrease in CG (or steady). Some cases displayed this in a very dramatic fashion leading to a more in–depth analysis of these cases in an attempt to find the reason for these changes to be so obvious in the lightning behavior.

On 13 May 2008, a large non–severe thunderstorm rolled over Dallas, Texas. The lightning count graph for this case is shown in Figure 25. The lightning jump noted in this event was classified as a hail type, as every radar parameter with the exception of maximum reflectivity showed large increases. The increase in VIL and VIL density in particular showed the strongest increases in value with the VIL jumping from a value of 30 to 50 and the VIL density showing much the same (Figures 26 and 27).

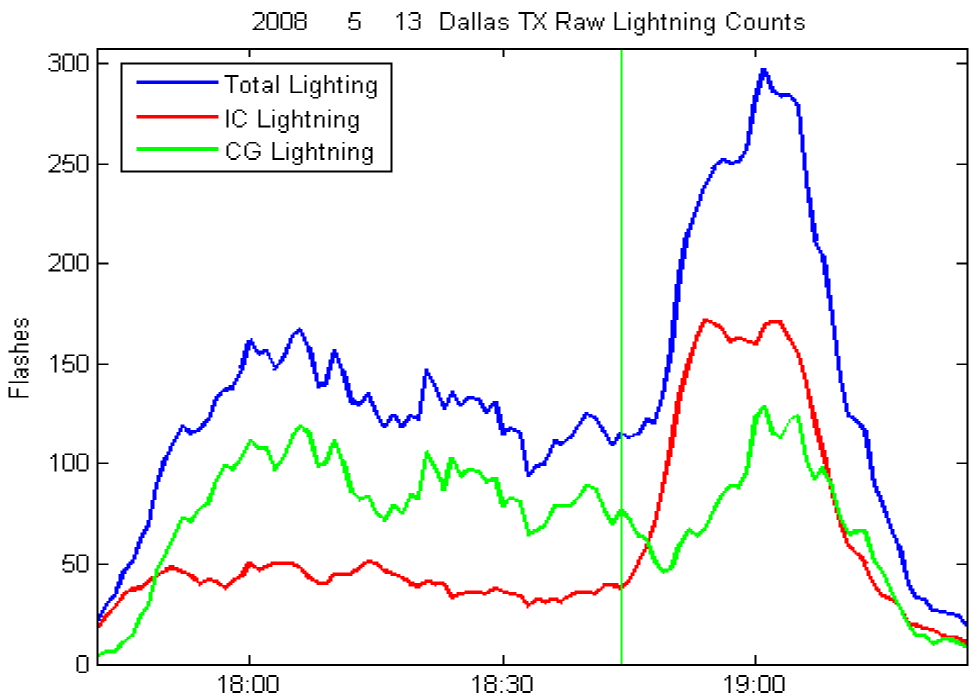

Figure 25. IC lightning dramatically jumps while CG suddenly drops, lightning jump (green vertical)

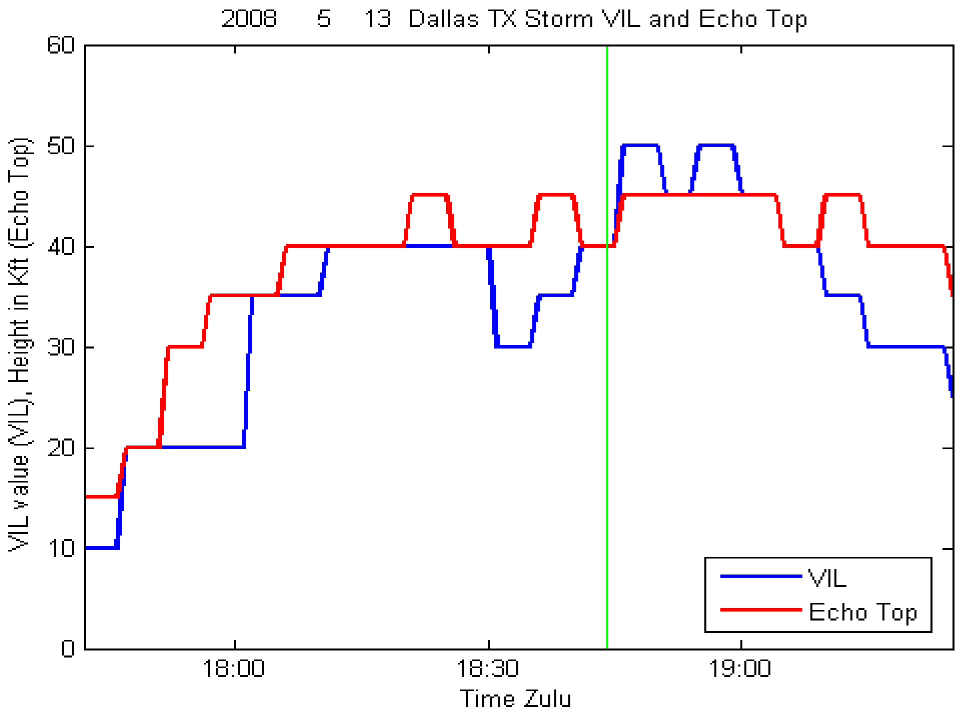

Figure 26. VIL values showing a very significant increase in value at the time of the jump. Lightning jump (green vertical)

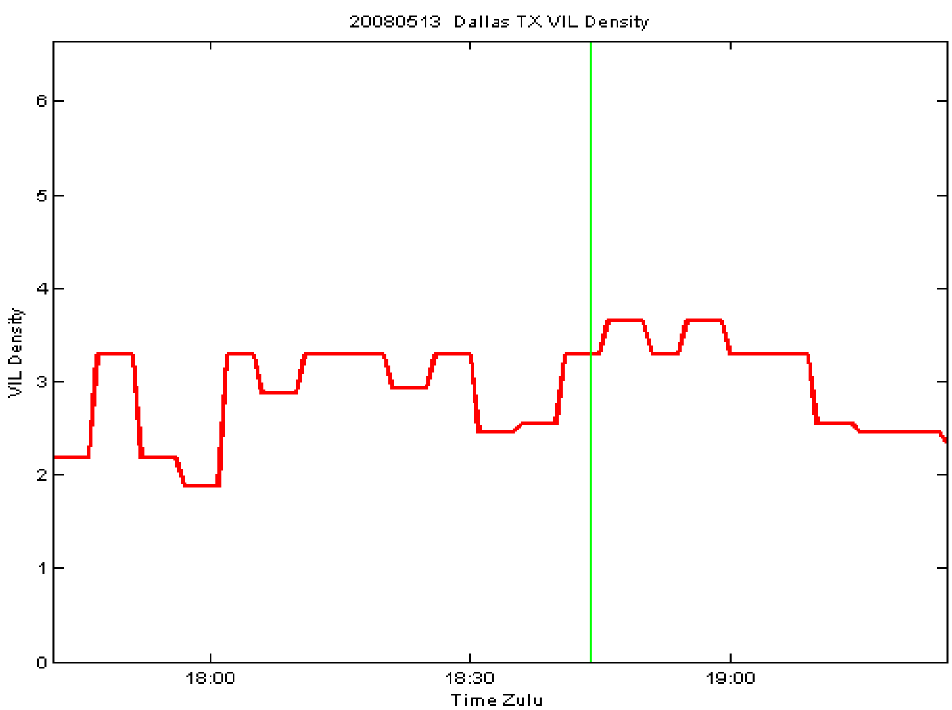

Figure 27. VIL density showing a similar jump in value at the time of the jump. VIL density (red trace), lightning jump (green vertical).

The sudden increases in the VIL and VIL density values, and the accompanying increase in the 55 DBz heights, are strong indications of a hail presence in the storm. This thunderstorm also maintained a maximum reflectivity of 65 DBz and an average DBz of 58.75 for the storms lifetime. The only other severe signature this thunderstorm maintained was a WER for 73 minutes of this storms life. Additionally, the WSR–88D hail algorithm projected the possibility of hail at 100% and the possibility of severe hail at 70% with a max hail size of 1”. The NWS office in Fort Worth issued a severe thunderstorm warning for this storm but, no severe hail reports were recorded for this event. Due to the high 55DBz, VIL and VIL density parameters, it is assumed this storm did contain hail but it was under the severe threshold. Unfortunately, there is no way to know if this storm did produce any hail at the ground and how much by ground truth. Hail sizes below ¾” are not reported or recorded in this part of the country as hail of this size is considered commonplace and not worth reporting. The Dallas, Texas case is the most obvious case to indicate the hail type lightning jump behavior between IC and CG lightning activity based on the presence of frozen hydrometeors. More importantly, sudden changes in the amount of the frozen hydrometeors are the likely culprits to the sudden increase in IC lightning and could be the reason for the observed trends in the hail type jumps.

Another non–severe case that also displayed strong hail signatures occurred on 31 July 2007 in Arva Valley, Arizona. In the Arva Valley case, the IC lightning production far exceeded the CG lightning to the point where the CG lightning could be considered insignificant. The Arva Valley storm also illustrates the point that a thunderstorm that is producing little CG lightning, which the NLDN only shows, could very well be overlooked at first by a forecaster due to the low amount of CG lightning. Figure 28 clearly shows that while the CG was low, the IC was not. The Arva Valley storm was also one of the highest lightning producers in the study.

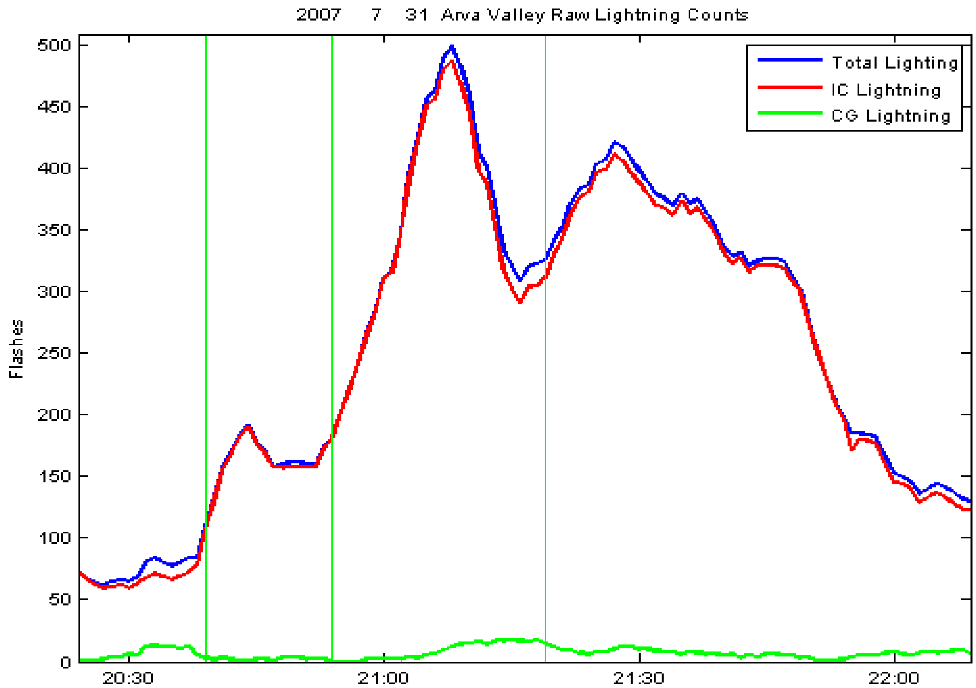

Figure 28. Arva Valley Non–Severe Lightning Counts. Lightning jumps (green vertical).

The first two lightning jumps were classified as hail type and the third was classified as mixed. The radar structures for the first two lightning jumps would have lead any operational forecaster to lean toward hail as there were significant increase in VIL, VIL density and 55DBz height. Figures 29–31 illustrate this fact. The significant changes in VIL, VIL Density and the 55DBz in the radar returns clearly indicate the presence of hail or some other form of frozen hydrometeor present at the time of the lightning jumps.

Figures 29–31 show the radar was indicating a strong hail signature for the Arva Valley storm. At the time of the first jump, the radar was indicating a possibility of hail of 100% and a possibility of severe hail of 10 percent and max size of ¾”. For the second jump the possibility of hail has dropped to 60 percent and the possibility of severe hail dropped to zero percent with a max size of ½”. Ground truth was not available for the Arva Valley case as the storm rapidly moved into unpopulated areas. The Arva Valley is another case in which the WSR–88D was showing significant hail signatures,

although it was not as aggressive as the Dallas, Texas case. The FMH–11 also clearly indicates these are hail indicators. The max reflectivity from both the Dallas, Texas and Arva Valley, Arizona cases were well above 55 DBz, which indicates the presence of frozen hydrometeors in the cloud. In Figure 29, the 55DBz height was rather variable but remained in the mixed phase layer between the WB0 (15036 ft) and the M20C (25345 ft) marks. The 55 DBz heights were clearly in this layer. Figure 29 does show the 55DBz height dipping below the WB0 height for one volume scan but then more than doubled its height right after the jump thus, giving it a significant net increase in height indicating an intensifying storm. VIL levels were also very high with levels in the mid 40 after the first jump and then into the mid 50s after the second jump. The Arva Valley case also indicates the hail type lightning jumps appear to be heavily dependent on changes in the amount, and composition of the frozen hydrometeors in the thunderstorm updraft column as all the greatest changes in the 55DBz height, VIL and VIL density were occurring in the area of the main updraft on radar.

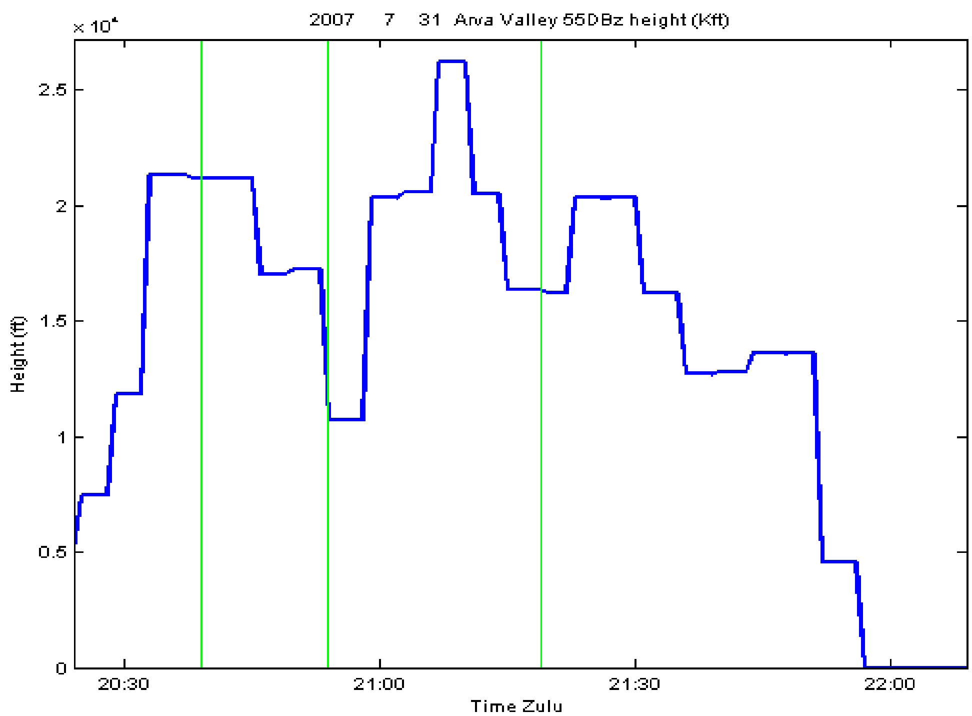

Figure 29. Arva Valley 55DBz height (blue trace), lightning jumps (green vertical).

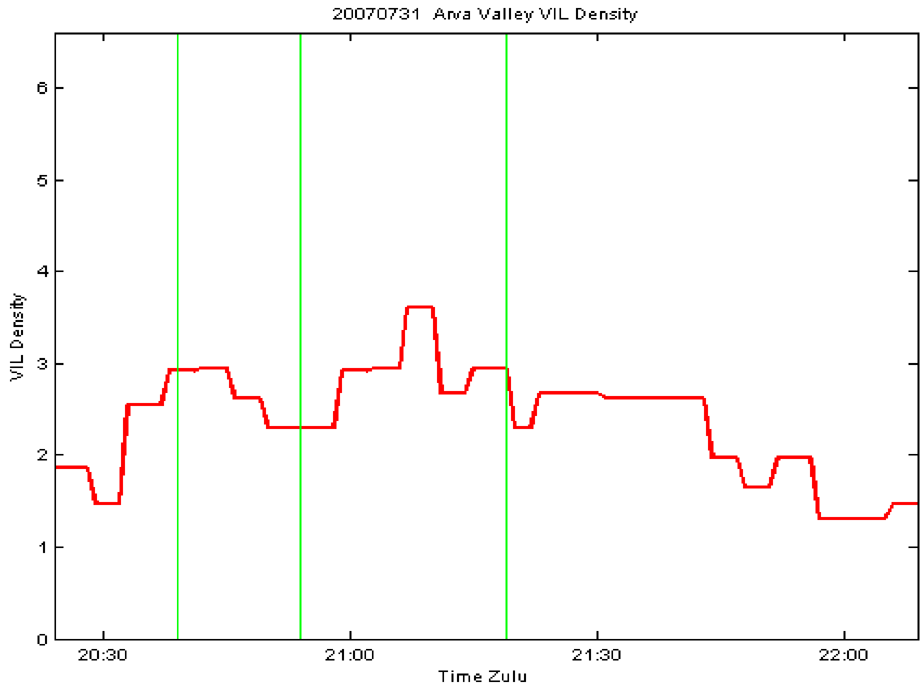

Figure 30. Arva Valley, Arizona VIL density (red trace), lightning jumps (green vertical).

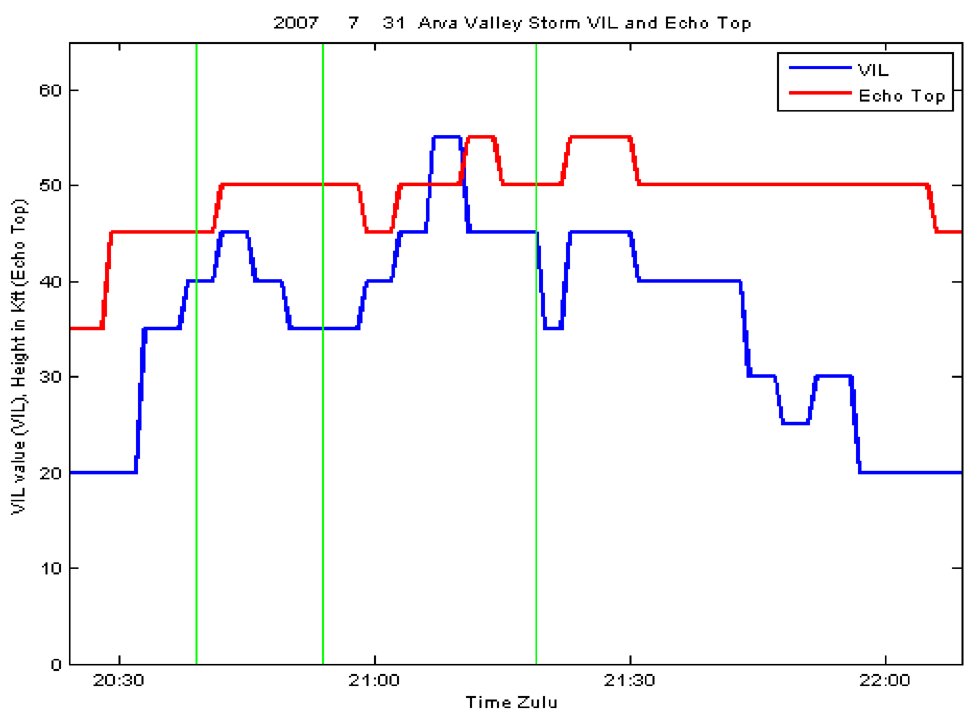

Figure 31. Arva Valley, Arizona VIL and Echo Top. Lightning jumps (green vertical)

6. Low Lightning Activity Storms

In this section, the low lightning activity storms were analyzed in an effort to determine if lightning jumps behaved differently and/or were dependent on different changes in the thunderstorm structure from the high lightning activity storms and severe storms. What was immediately apparent is the lightning jumps observed in the low lightning activity thunderstorms behaved the same way and were linked to the same changes in thunderstorm structures as the other cases. In this study, the threshold for thunderstorms with low lightning activity to identify a lightning jump was reduced to an increase of five lightning flashes in a one-minute period. Thunderstorms that failed to produce total lightning counts in excess of 150 flashes for a single six-minute period were considered low lightning activity thunderstorms. The reduction in the lightning jump threshold was deemed justified when it was noted these increases occurred in the same fashion as found in severe and high lightning activity cases.

Nine cases in this study were classified as low lightning activity thunderstorms. Of those, five produced severe weather, two produced hail and three produced wind. There were no low lightning activity thunderstorms in this study producing tornadoes, as was the case in a previous study by Shultz et al. (2009). All nine cases did produce lightning jumps. Past studies had their thresholds for identifying lightning jumps set too high for severe producing storms with low lightning activity to be identified (Shultz et al. 2009). This study took an approach of evaluating each storm based on its individual lightning activity, and then adjusted the lightning jump threshold to match. The reduced threshold approach allows the total lightning, IC lightning and CG lightning rates of increase, to be seen relative to each individual storm, as Figures 32–34 illustrate.

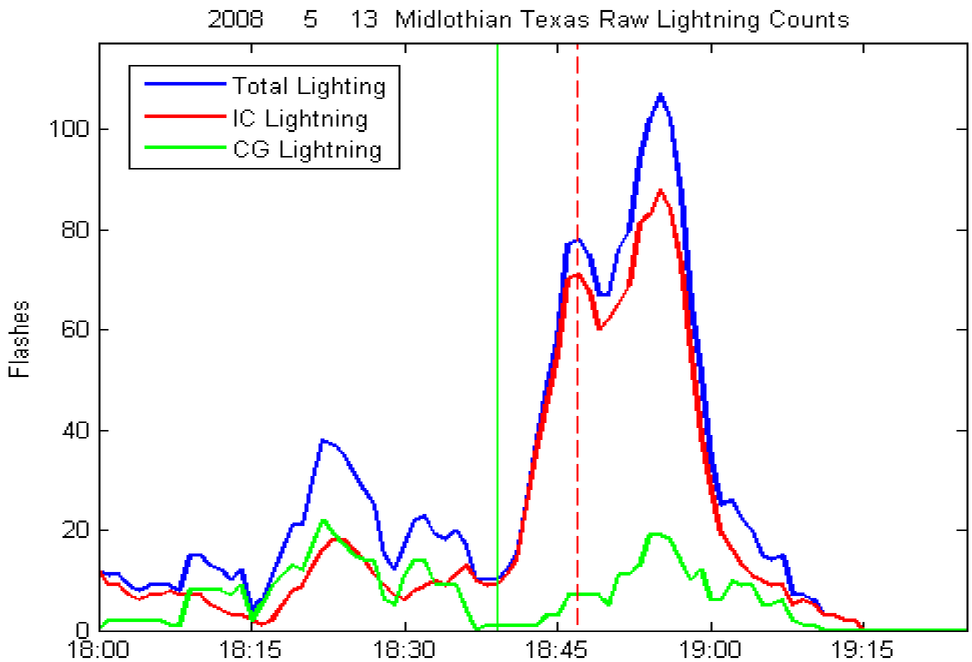

Figure 32. Midlothian, Texas low lightning activity thunderstorm. Lightning jump (green vertical), hail (dashed red vertical).

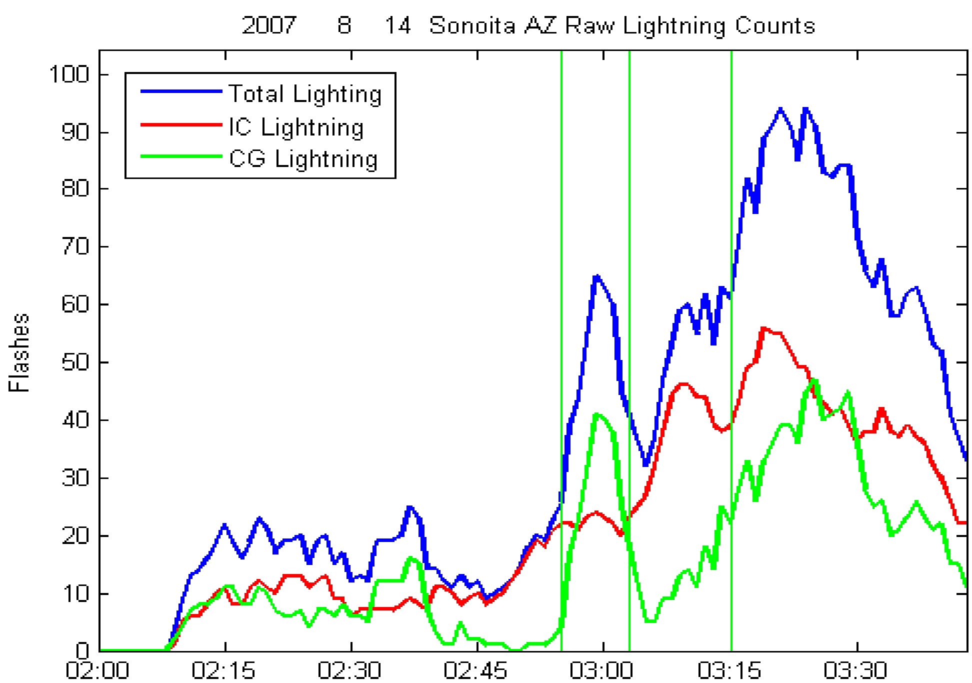

Figure 33. Sonoita, Arizona low lightning activity thunderstorm. Lightning jumps (green vertical)

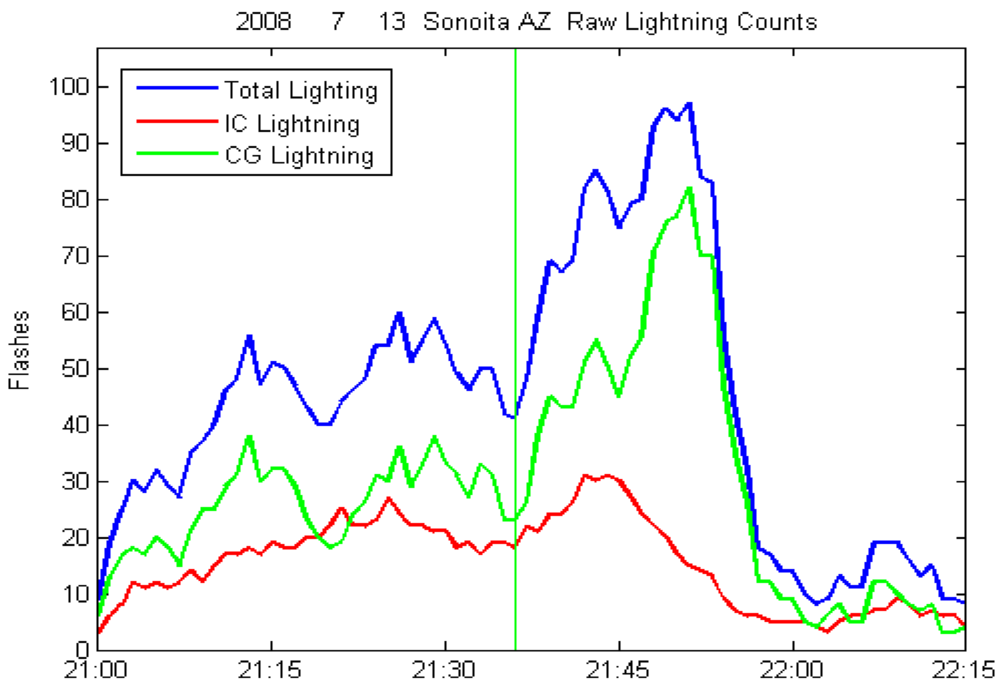

Figure 34. Sonoita, Arizona low lightning activity thunderstorm (second event). Lightning jump (green vertical)

Figures 32–34 show that each case has a much different lightning activity trace. The individual behavior in the lightning traces was found to be common among all the thunderstorms cases in this study. What seemed to be unique among the low lightning activity cases, was the relationship between the CG lightning and IC lightning. In the low lightning activity cases, the CG lightning frequently exceeded the IC lightning. On the other hand, when lightning jumps did occur, the IC and CG lightning characteristics tended to revert to the general pattern found and discussed earlier in this study. The fact the lightning jumps from the low lightning activity cases displayed the same behavior discussed in the high lightning activity and severe cases makes an important point to ensure that an operational forecaster looks at each thunderstorm's lightning activity individually and properly adjust the lightning jump threshold based on its current total lightning activity at the time. Figure 32 is from the Midlothian, Texas is a clear example. The steep slope only produced a rate of increase of 10 flashes two minutes prior to the severe event and would have placed the mark of the jump squarely in the middle of the increase while the lower threshold identified the jump a full five minutes earlier. The

time interval is critical as the lightning activity increase has to be sustained for at least three minutes before a lightning jump can be identified. Using the higher threshold of 10, the lightning jump would not have been identified until after the severe weather event or not at all. Using a five flash increase requirement, the lightning jump is identified five minutes sooner, or a full WSR–88D volume scan earlier, which is critical to severe weather warning decision making. Closer examination of the radar data at the time of the lower threshold's identification mark clearly show the storm was undergoing a significant intensification at that time, justifying the lower threshold. From this study, it is apparent the low lightning activity storms need to be treated differently and lightning jumps occurring from low lightning activity storms need to have a lower threshold as the changes in the thunderstorm are smaller in magnitude, and as such, more difficult to see and identify in real time. Every low lightning activity storm in this study displayed lightning jumps but the magnitude was smaller than the high lightning activity cases. Only one of the low lightning activity cases had a lightning jump that would have been identified using the higher threshold.

7. High Lightning Activity Storms

Like the low lightning activity cases, the high lightning activity cases were looked at separately to see if there was a distinct difference between the high lightning activity cases and the low lightning activity cases. The high lightning activity cases displayed a pattern indicating IC tended to be greater or far exceed the amount of CG lightning in the high lightning activity cases while the low lightning activity cases tended to have CG lightning closer to the IC lightning activity. There were some high lightning activity cases where CG lightning would parallel the IC lightning but not exceed it. Twenty–six of the 34 thunderstorm cases in the study fell into the high lightning activity category. Figures 35–38 illustrate the general pattern and the few outliers to this finding.

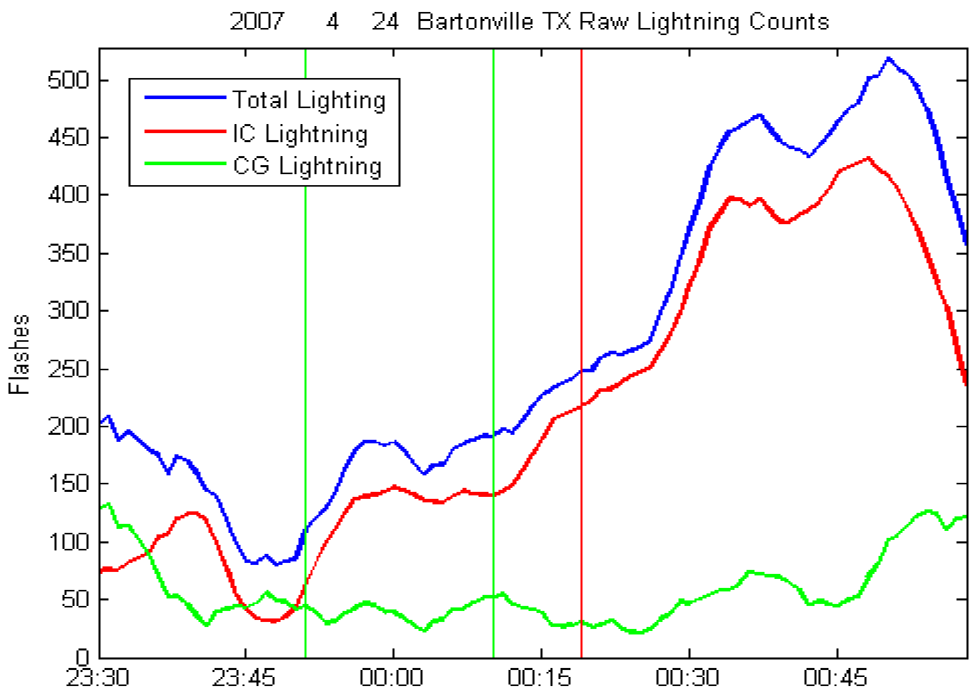

Figure 35. Bartonville, Texas High Flash Count Thunderstorm. Lightning jumps (green vertical) tornado (red vertical)

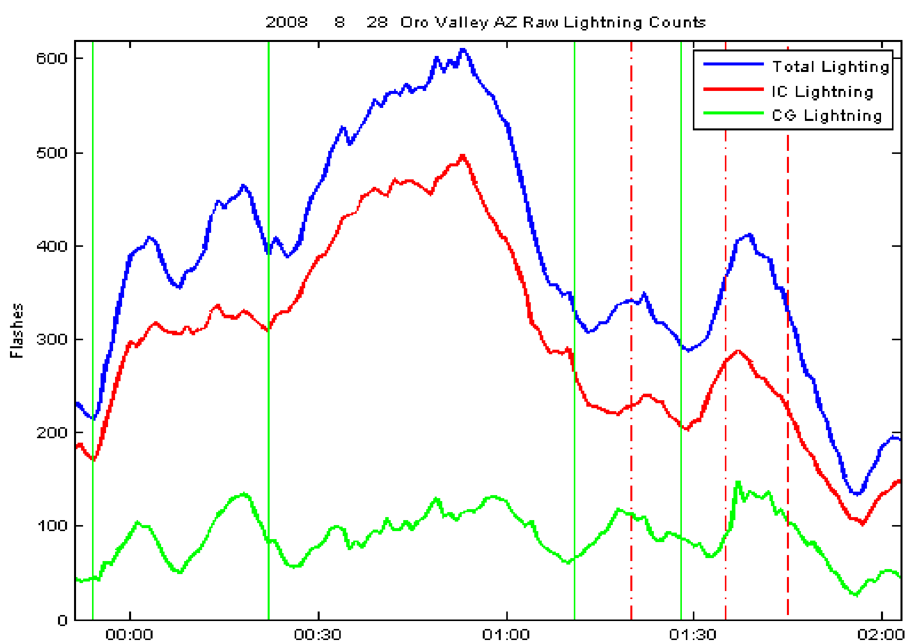

Figure 36. Oro Valley, Arizona High Lightning Activity Storm. Lightning jumps (green vertical), hail (dashed red vertical), severe wind (dashed–dotted red vertical).

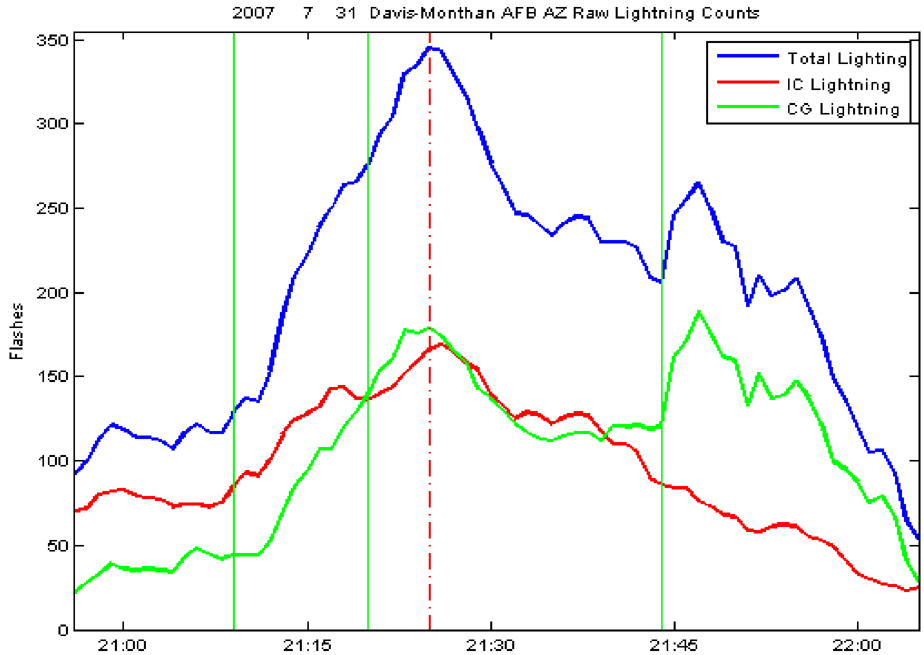

Figure 37. Davis–Monthan AFB, Arizona High Lightning Activity Thunderstorm. Lightning jumps (green vertical), severe wind (dash–dotted red vertical).

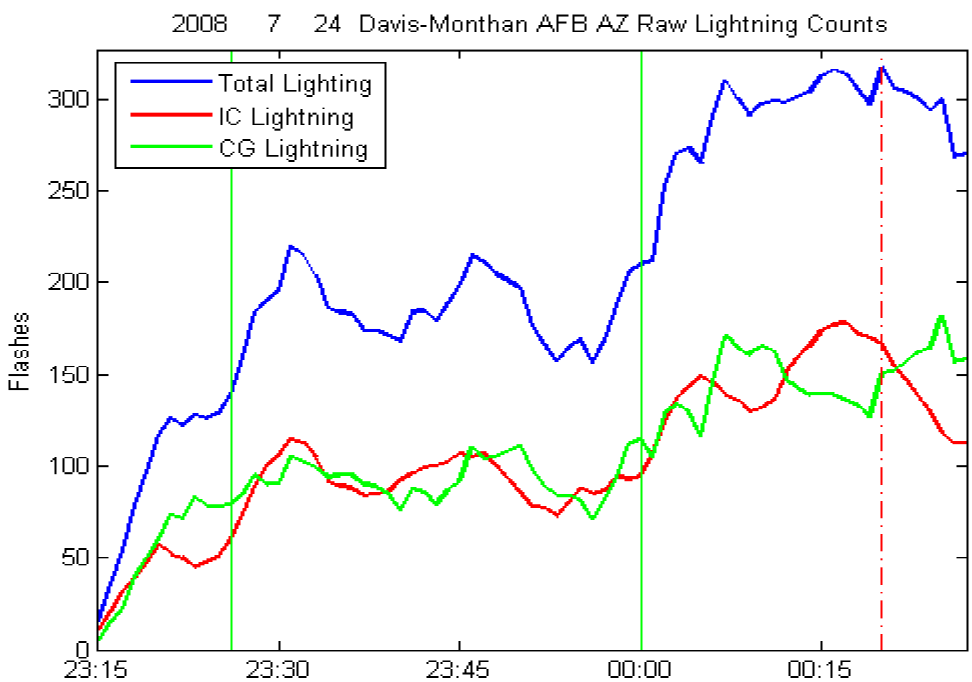

Figure 38. Davis–Monthan AFB, Arizona High Lightning Activity Storm (second case). Lightning jumps (green vertical), severe wind (dashed–dotted red vertical)

Figures 35 and 36 show the best example of the IC lightning being greater than the CG. The dominance of the IC lightning activity is in stark contrast to the low lightning activity storms where the CG was often greater than the IC lightning activity. There is one point in Figure 35 where the CG does exceed the IC for a short period of time, and this occurred in several of the high lightning activity cases. Of the enhanced CG compared to IC in the high lightning activity cases was always for a short period of time and was either during a period where lightning activity was low or high elevation played a role. Higher elevation only had an effect in the Arizona cases. The affects of higher elevation on CG lightning can be seen in Figure 36 where the CG lightning shows a very sharp increase after the last marked lightning jump. The sudden increase in CG was not classified as a jump as the storm's position on radar showed the cell to be over Mt. Lemon, Arizona, which has an elevation of 9,156 ft. The cloud base of the thunderstorm at the time the storm came into contact with Mt. Lemon was at 5,700 ft according to radar returns. This means the ground was now higher than the base, meaning the negatively charged cloud base no longer needed to build up a charge normally needed to break down the atmosphere to allow a lightning stroke. Higher elevation could also explain the wind report at the same time. Thus, a significant increase in CG lightning occurred at that time. Figure 37 shows that CG lightning can suddenly overtake IC lightning in a high lightning activity storm Figure 38 shows the one outlier in the high lightning activity cases. In Figure 38, the CG lightning was consistently very close to the IC lightning and at many times during the storm was greater than the IC lightning.

B. RADAR SIGNATURES/STRUCTURES AND LIGHTNING ACTIVITY

In this part of the study, an attempt was made to find any patterns between common thunderstorm parameters from the WSR–88D used to interrogate the severity of thunderstorms and lightning jumps. Specifically, are the lightning jumps a reaction to the parameters developing in a given thunderstorm, a precursor to or have no identifiable relationship to subsequent thunderstorms evolutions. Some problems became apparent in this section as many of the parameters were already present in the thunderstorm well prior to any of the lightning jumps, or were too few in number to make any sort of

relationship comparison. Storm top divergence showed no significant relationship to lightning jumps. The WER signature tended to show no significant relationship either but it should be noted that for many of the cases a WER was already present when the storm came into range of the lightning detection system. The TVS and BOW echo signatures could not be evaluated as there were too few cases to evaluate (TVS had four and BOW had two). Due to the limitations, storm top divergence, WER, BOW and TVS signatures could not be evaluated for direct relationships. The BWER, MESO, 55 DBz height, VIL and VIL density could as these signatures tended to occur near the time of the lightning jumps and were rarely already present when the storm entered the lightning detection system's range.

1. BWER and Lightning Jumps

The BWER signature is one of the more significant severe weather signatures operational forecasters look for in gauging the severity of a thunderstorm. Additionally, BWER signatures are well-known to be frequently present in severe hail and tornado producing storms. Previous studies have also shown the BWER to almost always be present when a lightning hole develops (Goodman et al. 2005; Steiger et al. 2007a). In this study, there were 15 cases displaying a BWER signature. In all 15 cases, the start of the BWER occurred within 15 minutes of the lightning jump with an average time difference of 7.4 minutes. This is very close to the time the WSR–88D takes to produce a complete volume scan. In three of the cases, the BWER occurred after the lightning jump, while in 12 of the cases, the BWER occurred before the lightning jump. Figures 39–41 show several cases where the BWER occurs very close to the time of the lightning jump.

Figures 39–41 indicate the development of a BWER in a storm does have a direct relationship to the lightning activity as the BWER is occurring within 15 minutes of the lightning jump with an average occurrence of 7.4 minutes of the lightning jump. Previous studies have shown lightning jump occurrence to be closely linked to the thunderstorm's updraft strength (Williams et al. 1999; Goodman et al. 2005; Steiger et al. 2007a). It is well-known the BWER signature occurs due to a very strong thunderstorm

updraft so finding the BWER signatures occur on average within 7.4 minutes of a lightning jump on average is expected. The BWER cases in this study also found that 12 out of the 15 cases the BWER occurred before the lightning jump, which could indicate the BWER tends to be a precursor to a lightning jump.

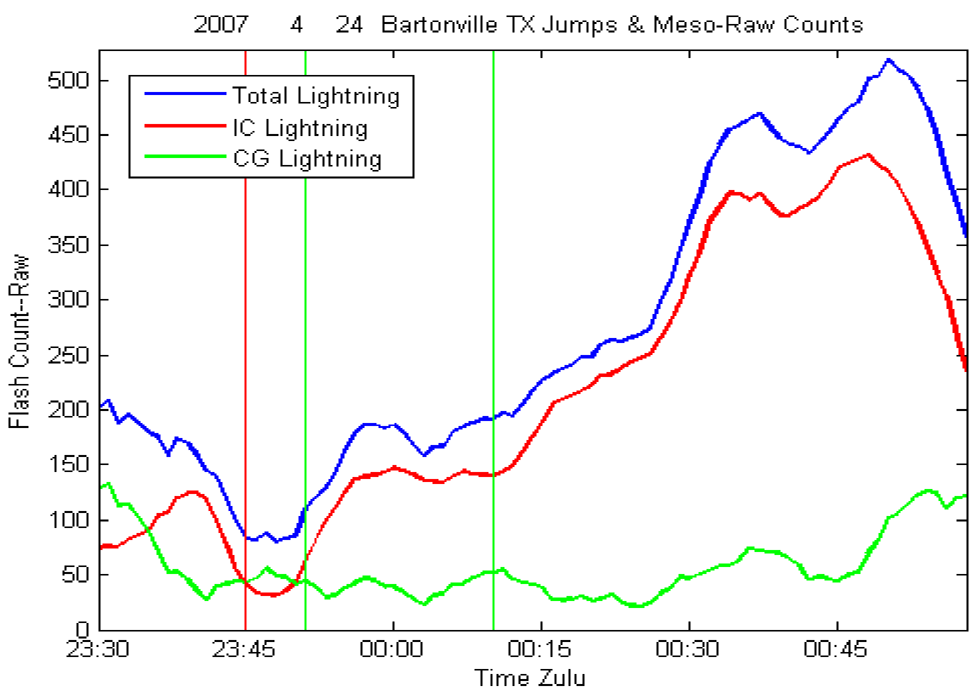

Figure 39. Bartonville, Texas BWER occurring 7 minutes Prior to Lightning Jump. Lightning jumps (green vertical) BWER (red vertical).

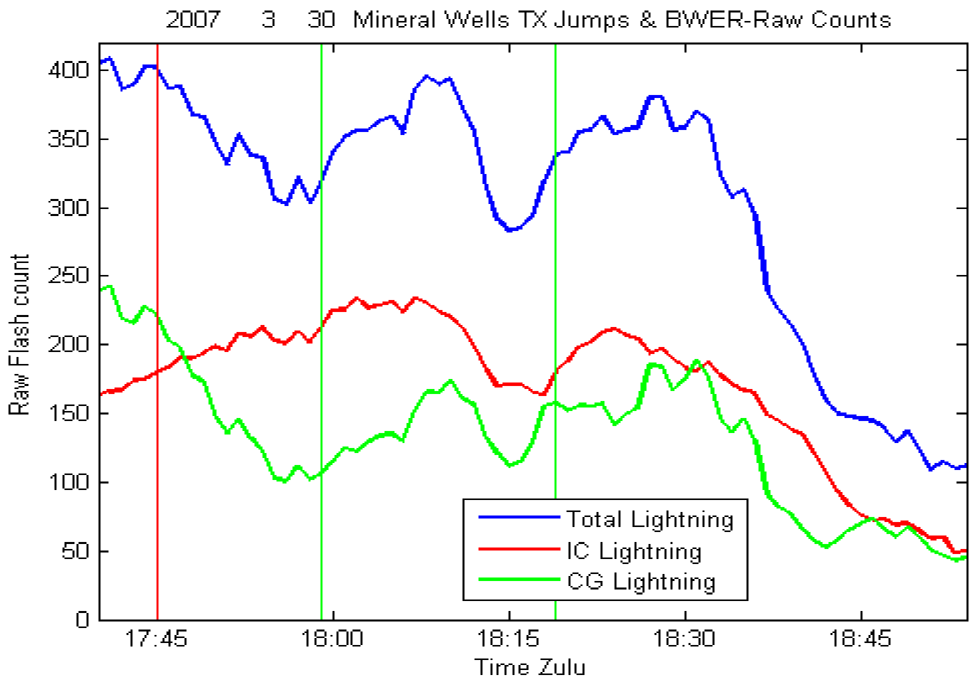

Figure 40. Mineral Wells, Texas BWER occurring 14 minutes prior to Lightning Jump. Lightning jump (green vertical), BWER (red vertical).

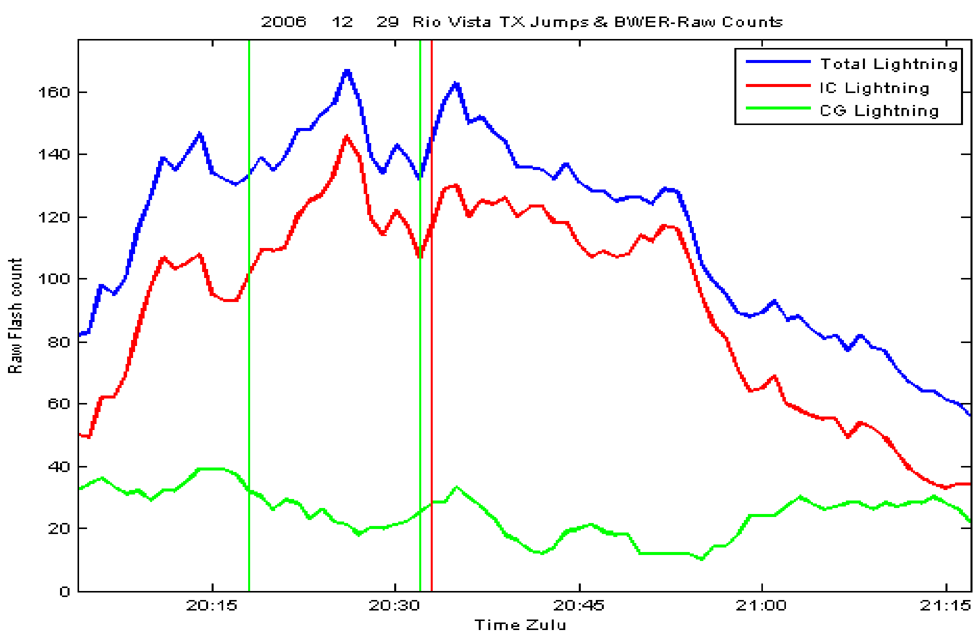

Figure 41. Rio Vista, Texas BWER Occurring one minute after Lightning Jump. Lightning jump (green vertical), BWER (red vertical).

2. Mesocyclone Signatures and Lightning Jumps

The mesocyclone signature is another radar parameter looked at closely for a relationship between it and lightning jumps within a thunderstorm. The MESO parameter was carefully looked at to make sure there was enough evidence on radar to classify a mesocyclone, and was done in accordance with the NWS FMH–11. The FMH–11 requires a minimum of a 20Kt difference between the in and out bound maximum wind and to be at three consecutive levels and be sustained for at least two volume scans. Twelve storms met the criteria for at least two volume scans. The mesocyclone parameter showed the same correlation between its onset and lightning jumps as the BWER signature. All 12 occurred within 15 minutes of a lightning jump with an average of 9.53 minutes. The correlation was not as close as the BWER, but it is close enough to indicate there is a relationship between the mesocyclone formation and lightning activity in the storm. Figures 42–44 illustrate the close proximity the mesocyclone onset to the lightning jumps.

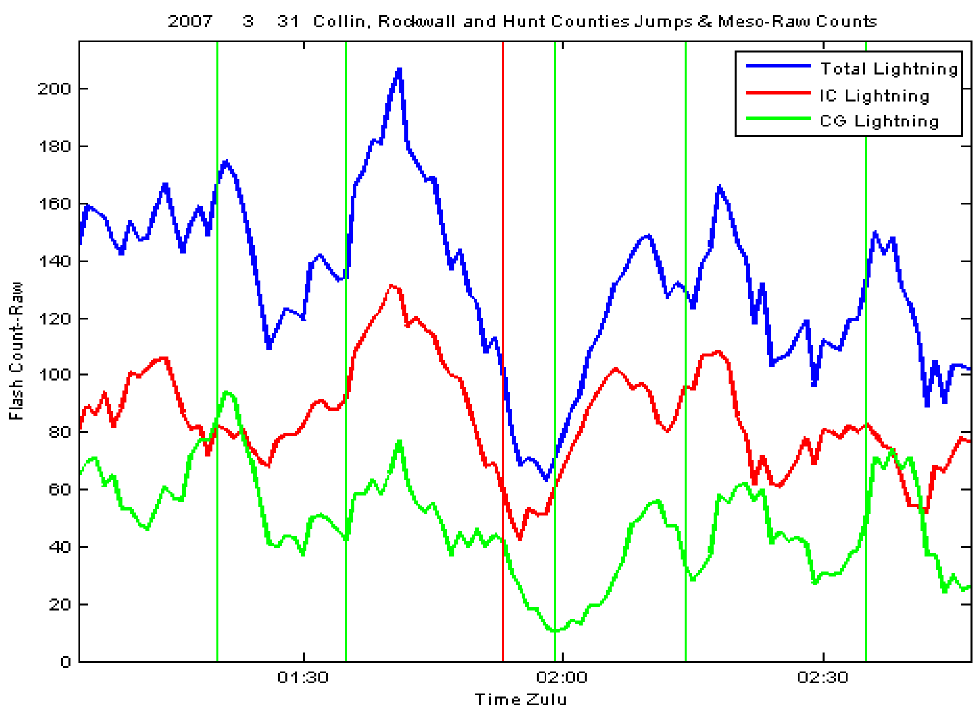

Figure 42. Collin, Rockwall and Hunt Counties MESO signature 5 Minutes Prior to Lightning Jump (green vertical), MESO (red vertical).

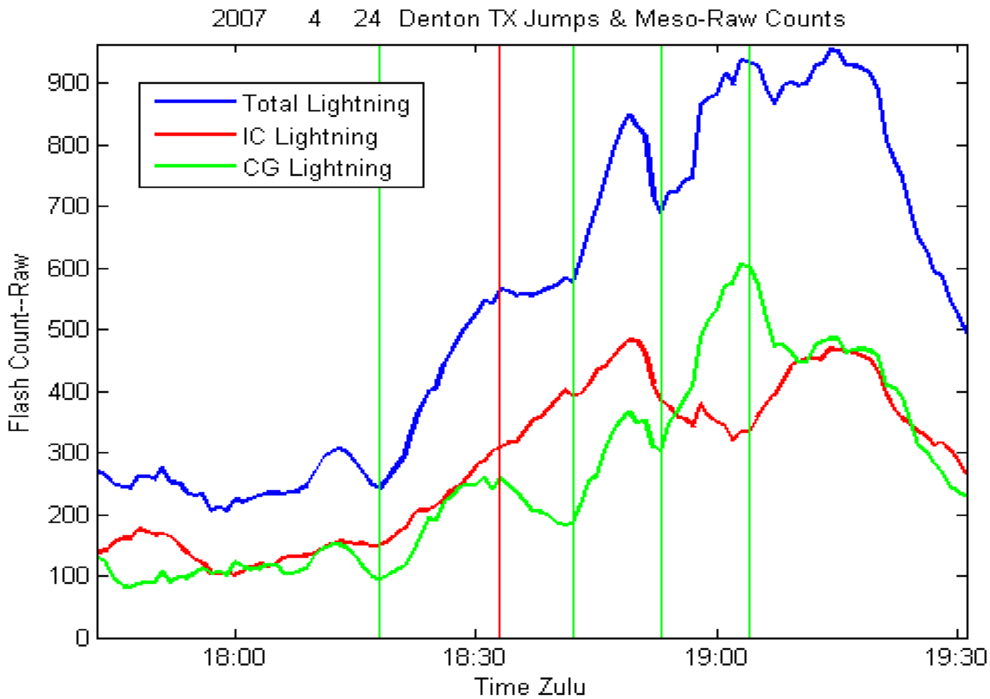

Figure 43. Denton, Texas MESO Occurring 11 Minutes Prior to Lightning Jump. Lightning jump (green vertical) MESO (red vertical).

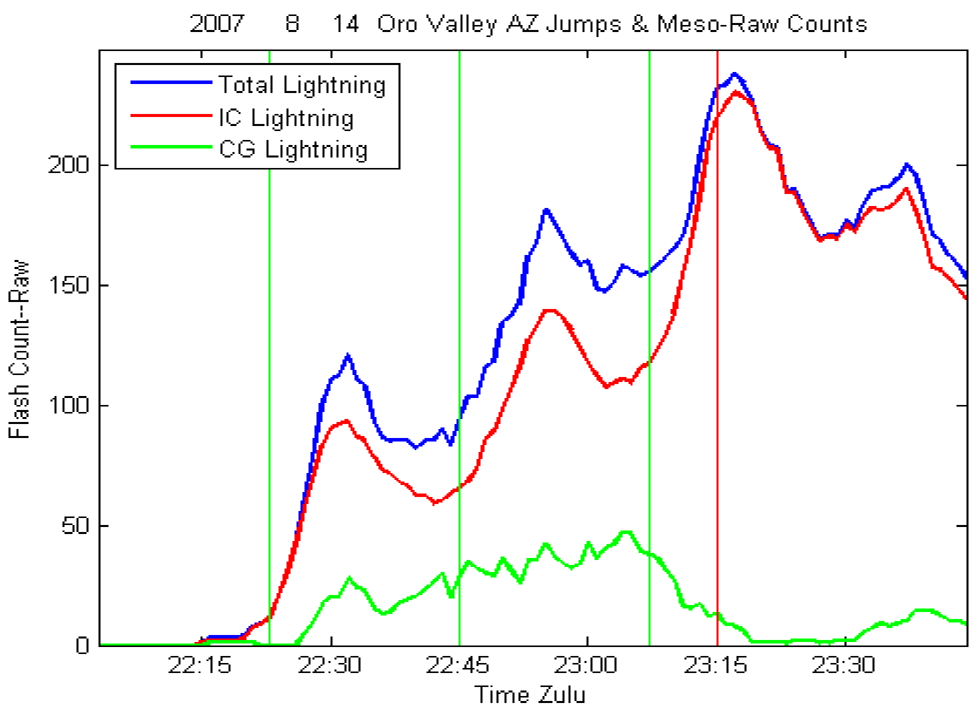

Figure 44. Oro Valley, Arizona MESO Occurring 10 Minutes After Lightning Jump. Lightning jumps (green vertical), MESO (red vertical).

Since Mesocyclones are also well-known to occur with severe hail, wind and tornado events, its stands to reason that, like the BWER, the MESO signature would occur near the lightning jumps. This study also shows the MESO signatures are directly related as in every case, the mesocyclone started within 15 minute of a lightning jump. In eight of the 12 cases, the Mesocyclone starts prior to the lightning jump, which suggests the lightning jump occurs in reaction to the mesocyclone development. The sample is too small to definitively conclude the observed behavior is a reaction as in four of the MESO cases the MESO signature occurs after the lightning jump. A possible reason for the tendency of the MESO signature to be detected first is the turning of the thunderstorm itself. As the thunderstorm rotates, the charged areas are also rotating around the storm, and as they do, they interact with the updrafts and downdrafts within the storm likely moving the charged regions around. The movement of the charged regions to areas that are predominately of the opposite charge will cause a sharp increase in lightning activity.

3. 55DBz Height, VIL and VIL Density and Lightning Jumps

There are roughly six radar parameters commonly used by operational forecasters to determine the severity of a thunderstorm. These parameters are: maximum reflectivity, 55DBz height, VIL, Echo Top, VIL density and Wind Gust Potential (WGP). Of these six parameters, only 55DBz height, VIL and VIL density showed a significant relationship between them and lightning jump activity. It is surprising that Echo Top did not show a stronger relationship with lightning jump activity as VIL density uses both VIL and Echo Top to determine its value and is thus, very sensitive to Echo Top. The lack of a relationship between Echo Top and lightning jump duplicates the finding by Williams et al. (1999) that max lightning activity does not correspond with max cloud top. VIL density however does require VIL to have a higher numerical value than Echo Top for VIL density to reach severe levels above three, and especially 3.5, which is considered the lowest value for an increased likely hood for severe hail (Technical Note 98–02). The worst parameter of the six was WGP. WGP failed to show any relationship with lightning jumps for all 34 thunderstorm cases and even worse, failed to indicate severe wind in all 25 severe cases studied in this thesis.

Earlier in this thesis, 55DBz, VIL and VIL density were grouped together and required to have more than one of them displaying the same behavior when classifying the individual lightning jumps. Here, they are evaluated individually in an attempt to see if there is any direct relationship between 55DBz, VIL and VIL density and lightning jumps.

a. 55DBz Height

The 55 DBz heights were examined in 31 of the 34 cases. The other three could not be included as one had errors in the in the 55 DBz height data and two were too close to the WSR–88D at the time of the lightning jumps where the cloud tops was artificially low and could not be determined. In the 31 cases, there were 69 lightning jumps. Sixty–four of the lightning jumps either preceded or followed a significant increase or decrease in 55DBz height being detected on radar within 10 minutes of the lightning jump. For the other five jumps, there was either an increase or decrease in the 55DBz height on the radar but it was considered to be too small to be significant. A significant increase or decrease was defined at 1000 ft in one volume scan. For the five cases in which the 55DBz height changes were considered too small to be significant, it is important to note that all five occurred when the 55DBz height was at or above 20,000 ft. This high height is significant as it was very close to the -20°C level in nearly all cases. The very cold temperatures at this height could explain why the changes in the height were not as significant as the 55DBz height may have already been at the maximum height possible for that particular storm. Figures 45–47 illustrate these increases and decreases.

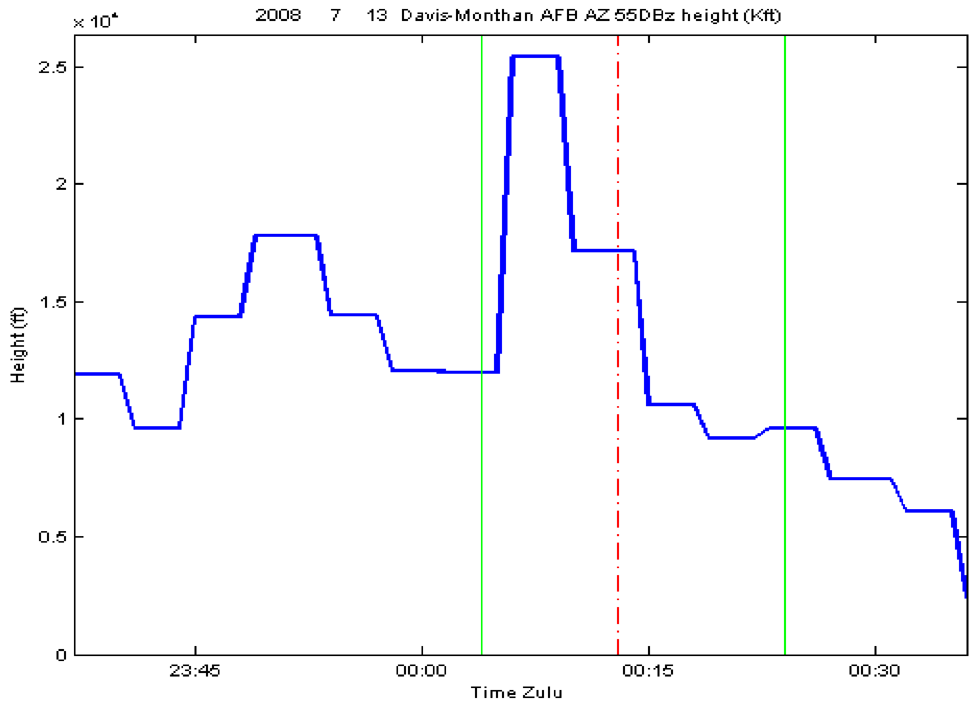

Figure 45. Davis–Monthan AFB, Arizona Lightning Jumps and 55DBz Height. 55DBz height (blue trace), lightning jump (green vertical), severe wind (dash–dotted red vertical).

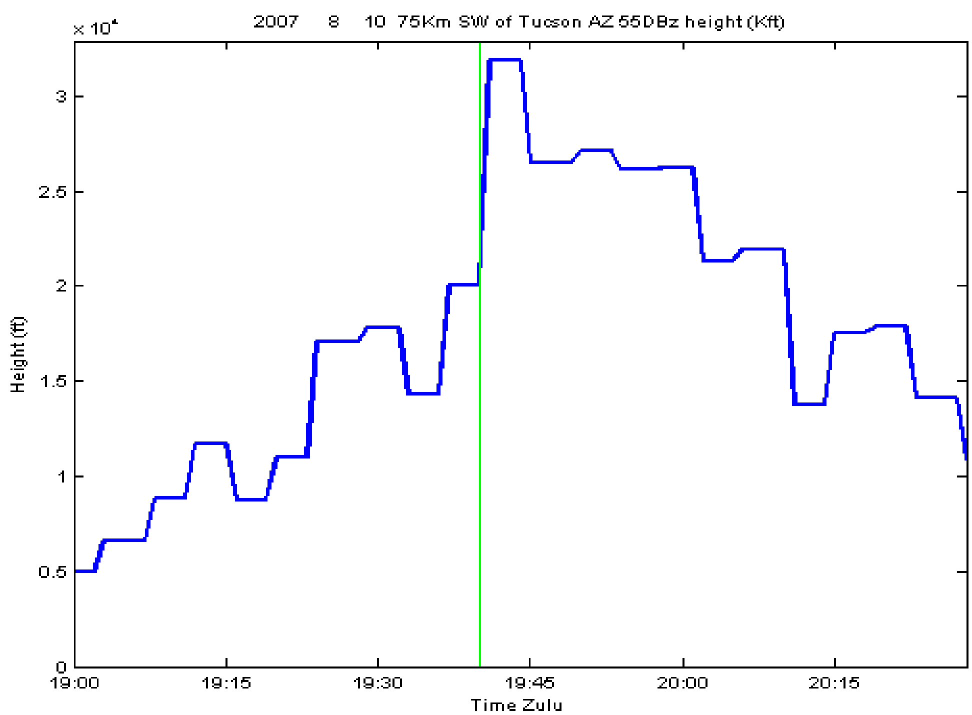

Figure 46. Non–Severe Event Southwest of Tucson with Lightning jump and 55DBz Height. 55DBz height (blue trace), lightning jump (green vertical).

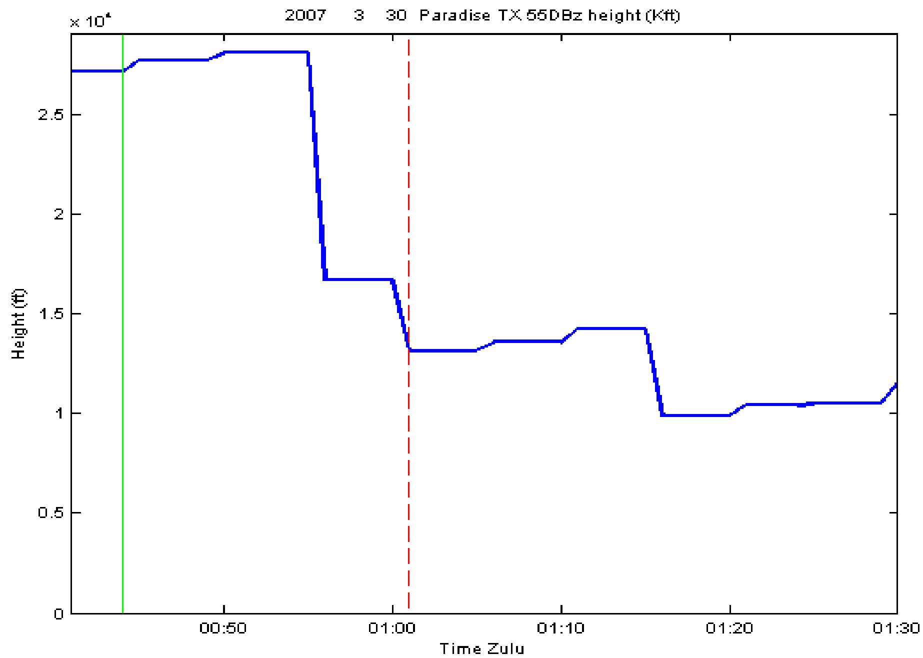

Figure 47. Paradise, Texas Lightning Jumps and 55DBz Height. 55DBz height (blue trace), lightning jump (green vertical), hail (dashed red vertical)

Figures 45 and 46 show a very significant change in the 55DBz height. Figure 47 shows a much smaller change in the height and is considered not to be significant. The height of the 55DBz reflectivity in Figure 47 is well over 25,000 feet though. The 55DBz height being over 20,000 ft was the case in all five of the lightning jumps that occurred near an insignificant increase/decrease in 55DBz height. In the 69 lightning jump instances, 57 of the lightning jump events were in close proximity of an increase in the 55DBz height while 12 were in proximity of a decrease. This yields a 4.75:1 ratio of the 55DBz height increasing when a lightning jump occurs. The preponderance of the 55DBz height increasing indicates there is a direct relationship to the 55DBz height rising at the time of a lightning jump. This reasoning is based on the knowledge that previous studies have indicated that charged areas of the cloud can be advected to other areas of the cloud by the updrafts and downdrafts within the thunderstorm (Steiger et al. 2007a, b; Montanya et al. 2008). Meaning the charged areas can be advected up or down into an area of the cloud that has a high concentration of the opposite charge, triggering a large increase in IC lightning and then sustained long enough to be considered a lightning jump.

b. VIL and VIL Density and Lightning Jumps

VIL values are heavily used by the operational forecasters, as it has been shown that rapid changes, especially increases, in VIL indicate a storm is intensifying and hail is present. Additionally, high values of VIL generally indicate a very dense column of water or ice present in the storm (FMH–11, Technical Note 98–02). VIL density is another parameter used by the USAF and takes into account Echo Top. Thunderstorms with VIL density values over 3.5 are considered to be at risk of having large hail while VIL density values over 4 are considered to be high risk for having large hail. Due to the similarities between VIL and VIL density, these are examined together.

For the VIL and VIL density parameters, there were 73 lightning jumps to examine. In the VIL case, 49 showed a rise in VIL near the jump, while 17 showed a decrease and 7 did not show any net change at all. VIL density showed something similar with 46 jumps showing an increase, 24 showing a decrease and only three showing no change at all. Given the results of the VIL and VIL density and lightning, it is difficult to say if a lightning jump is either the result of or reacting to an increase in VIL value or VIL density. It can be said that lightning jumps are related to changes in VIL and VIL density. Additionally, VIL density appears to be more sensitive as there were less than half as many cases where there was no change in VIL density near a jump than VIL.

Figure 48 shows both an increase and a decrease in close proximity to a lightning jump. Figure 49 shows a VIL value remaining steady near a lightning jump and then a decrease. Figure 50 is taken from the same case as Figure 49 and shows the VIL density changing in close proximity to both lightning jumps. The behavior in Figures 48–50, indicate a relationship between the sudden increases in lightning activity and in VIL and VIL density values. Like the 55DBz parameter, specific increases or decreases VIL and VIL density could not be considered a precursor or reaction although increases in VIL and VIL density tended to follow a lightning jump.

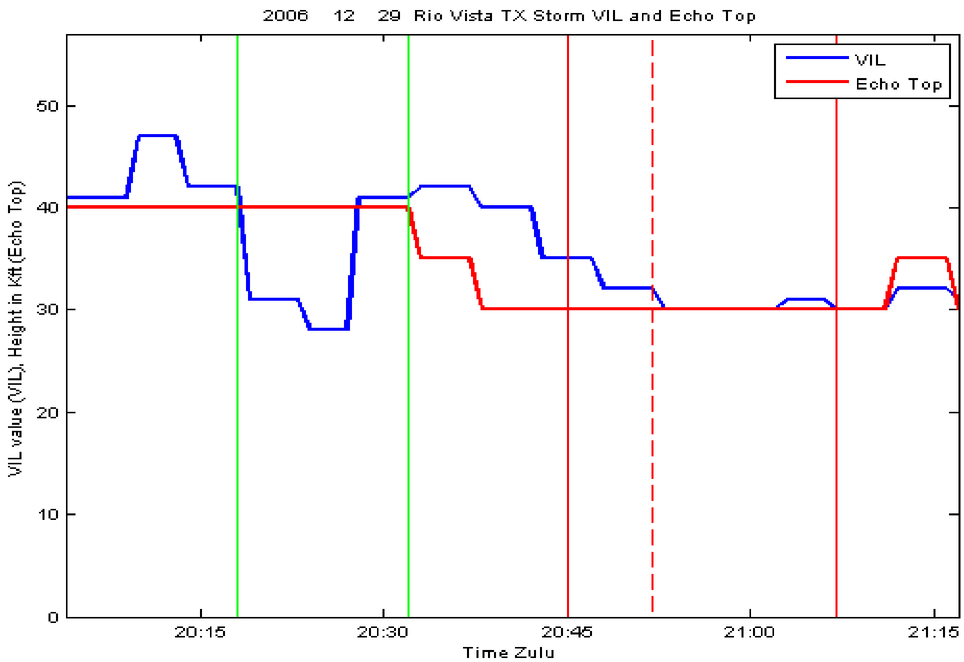

Figure 48. Rio Vista, Texas Both Increases and Decrease in VIL near Lightning Jumps. Lightning jumps (green vertical), tornado (red vertical), hail (dashed red vertical).

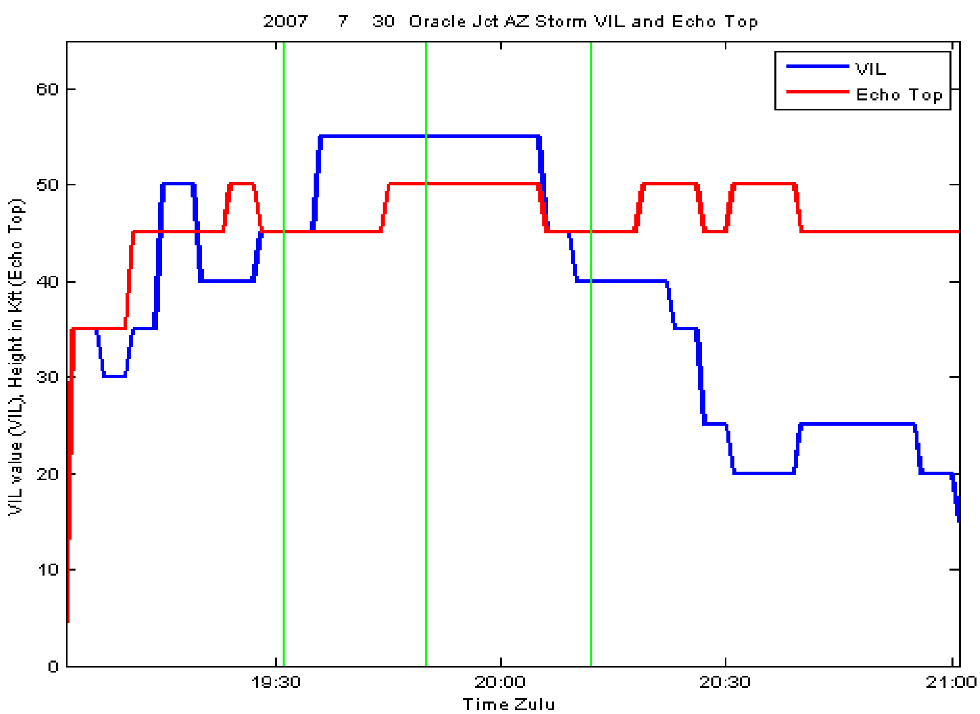

Figure 49. Oracle Jct, Arizona with no Change in VIL and a Decrease in VIL. Lightning jumps (green vertical).

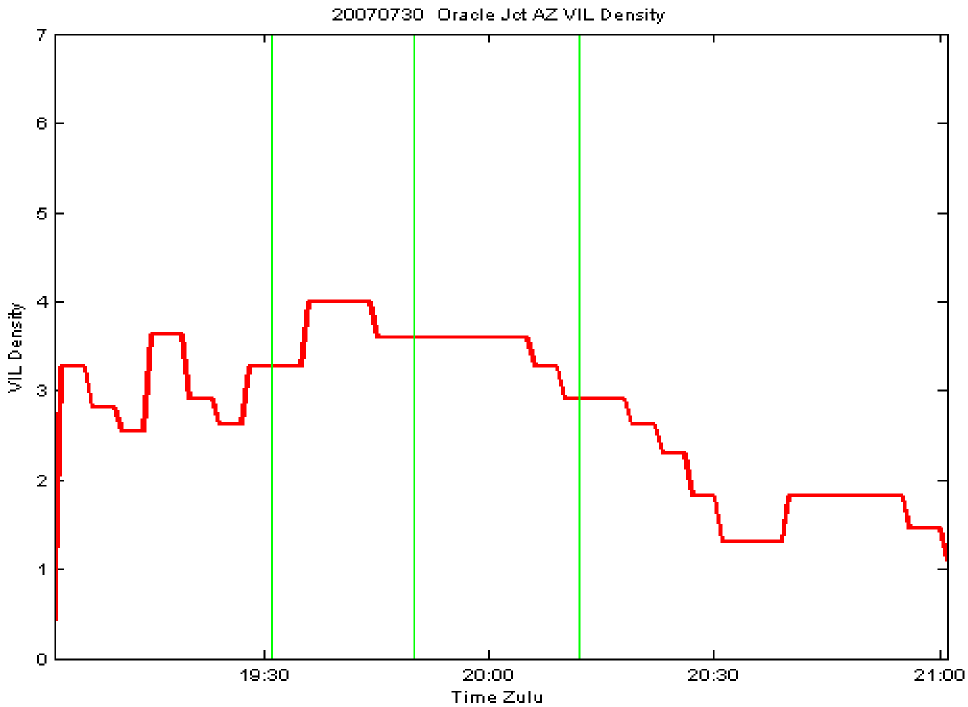

Figure 50. Oracle Jct, Arizona with Two Decreases in VIL density. Lightning jumps (green vertical).

C. SOUNDING DERIVED STABILITY INDEXES

This part of the study attempts to find any relationship between the currently used stability indices and the frequency of high lightning activity. The average time difference from the time of the sounding and the occurrence of thunderstorms in the KDFW area was five hours. For the KDFW area, there were several 18Z soundings preformed that greatly aided in reducing the average time difference. For the KTUS area, there were no 18Z soundings available, but most storms occurred near the 00Z sounding, which produced an average time difference to around four and half hours. One of the surprising results was observation that both the KDFW and KTUS regions showed the same tendencies when it came to the stability indices. The CAPE, SWEAT, SI, LI, K and three sounding derived levels of the WB0, M20C and the MPLT were studied. The sounding derived levels were separated into severe and non–severe cases and high and low lightning activity cases. There are many different opinions on which stability indices are the best to use and what values are considered critical. For this study, the critical values were taken from the USAF Technical 98–02 and are as follows: CAPE >1000, SWEAT

>275, K>30, SI and LI <0. The MPLT split into two categories with MPLT<10000ft and MPLT>10000 ft. The MPLT was looked at and assumed the larger your MPLT is, the greater the volume the thunderstorm had to develop and maintaining frozen hydrometeors.

One of the surprises in this part of the analysis was how poor the CAPE performed. In the 34 thunderstorm cases of this study, the CAPE only managed to exceed 1000 J/Kg in eight of the cases and then the highest CAPE value was 1732 J/Kg. In fact, there were ten severe cases where hail was the primary severe weather element and the CAPE was below 100 J/Kg and in some cases it was 0 J/Kg. This may indicate the amount of available potential energy from the potential buoyancy of the atmosphere may have no bearing on the atmosphere's ability to develop graupel and hail within a thunderstorm. As such, the amount of CAPE may also have no bearing on the thunderstorms ability to produced intense IC lightning activity.

Three indices that performed well, especially when all three were indicating the potential for high lightning activity, were the LI, SI and SWEAT. The LI and SI together performed very well as 24 of the 34 cases where there were high lightning activity storms the two indices were below zero. The SWEAT index by itself, had 15 out of 25 (severe only) cases where it was over 275 and high lightning activity storms were produced. In cases where the SWEAT was over 300, lightning activity tended to be the highest. Another interesting aspect was that in the nine low lightning events, seven of those events had SWEAT indexes below 300. Two events where the SWEAT was above 300 took place on the same day, one was severe and the other was not. The SWEAT that day was 422 and the severe event was the Midlothian, Texas event on 13 May 2008 that produced 1" hail.

The Mixed Phase Layer Thickness failed to show any relationship between the amount of lightning and lightning jumps. The severe cases showed a nearly equal number of severe cases with MPLT greater than 10Kft as it did cases with MPLT less than 10 Kft. When the MPLT comparison was done for the non–severe cases though, it produced the surprising result of having all nine non–severe cases with a MPLT greater than 10Kft. The result of the MPTL being greater than 10,000 ft for all the non-severe

cases was the exact opposite of what was expected. The large MPLT result seems to suggest that a smaller MPLT is more conducive to severe weather rather than a larger volume. It should be noted, however, that in all 34 cases examined, the WB0 height was above 10,000ft, which is considered to be very high. It has been empirically shown that WB0 heights 5,000–9,000 ft are ideal for hail occurrence on the ground. As such, this study could not evaluate storms with the WB0 levels in this critical range (Technical Note 98–02). The MPLT results only indicate the thickness of the mixed phase layer seems to have no affect on the thunderstorms preponderance for high or low lightning activity or its preponderance to produce severe weather.

The K index, which is primarily used to gauge heavy precipitation from convection rather than severity, was conflicting. In the 25 severe cases, the K index was over 30 in all but two of them. For the non–severe cases, eight of the nine non-severe cases had a K index over 30. For the nine low lightning activity storms, seven had a K index over 30 while for the 25 high lightning activity cases, 22 had a K index over 30. The K index results indicate no significant pattern or predictability of high lightning activity storms or low lightning activity storms.

Given stability index results, there does not appear to be any significant usefulness of the stabilities indices to predict the preponderance of thunderstorms to produce high amounts of lightning activity. The one exception appears to be the SWEAT index, which did show some skill. The SWEAT's skill is likely due to the fact the SWEAT index is highly dependent on the presence of cyclonic shear. Prior studies have indicated that IC lightning is highly dependent on cyclonic shear (Steiger et al. 2007a).

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V. SUMMARY AND RECOMMENDATIONS

This study confirmed that lightning jumps tend to precede the occurrence of severe weather on the ground and tornado-producing storms can have very high IC lightning production (Goodman et al. 2005; Shao 2006; Montanya et al. 2008; Pierce 1977; Williams et al. 1999; Steiger et a. 2007a). By looking into the individual behavior of the IC and CG lightning activity for each individual storm, a more specific relationship between lightning behavior and severe weather was obtained.

A. LIGHTNING JUMPS

This study has shown that hail events tended to be preceded by a lightning jump in which the IC lightning would increase while the CG lightning decreased or remained steady. Severe wind events tended to be preceded by lightning jumps in which both IC and CG would increase or the IC would decrease or remain steady while the CG increased. When the individual lightning jumps were compared directly to the radar-derived structures of the storm at the same time, a larger and more predominate pattern emerged. The comparison of lightning jump behavior and radar derived structures was a significant expansion from the study by Goodman et al. (2006) that found that the BWER radar signature was closely related to lightning holes. The comparison was also an expansion on the study by Steiger et al. (2007a), which showed a strong relationship between changes in VIL and lightning jumps. In this study, separating the lightning jumps into three distinct categories defined by the changes in the respective radar signatures yielded a stronger pattern. The hail type jumps showed as strong tendency to produce a lightning jump in which the IC lightning increased and the CG lightning decreased or remained steady. The hail type jump also preceded 14 of the 18 (77.78% of the time) severe hail events. Of the 34 hail type jumps, 25 (73.5% of the time), the lightning behavior displayed an increasing IC while CG was decreasing or steady. The IC increase while CG decreasing or steady relationship between the hail type jump and the occurrence of severe hail is consistent since the hail type jump. These lightning jumps were as hail type jumps when the radar signatures were displaying hail indications

like a rapidly increasing VIL, VIL density or an increasing 55DBz height. Many of the hail type jumps also occurred in close time proximity to the development of a BWER signature, which has been noted to occur frequently with lightning holes (Steiger et al. 2007a). Since a lightning hole is associated with an updraft so strong that the center of the updraft becomes a mono–charged area, and thus becomes void of lightning activity, a lightning jump would occur at the same time due to a significant increase in lightning activity around the periphery of the updraft (MacGorman et al. 2002; Steiger et al. 2007a). It should be noted, there were three severe wind events that occurred directly following a hail type lightning jump. Two of these events occurred within six minutes of the hail event and were likely caused by the large mass of hail falling out of the thunderstorm at the same time. The other one could not be explained but, if there was a large amount of non–severe hail falling at the same time that did not get reported since it was under the severe threshold, this offers a plausible explanation. The non–severe cases clearly indicate the hail type lightning jump was not unique to only severe hail size but likely due to a significant amount of frozen hydrometeors in the cloud at the time and was deduced by the hail signatures (high VIL and VIL density readings) present on the radar. In the high VIL and VIL density non–severe events, the hail were either not large enough to be considered severe when it hit the ground or melted completely before hitting the ground. The melting hail was likely because the WB0 height in all cases was above 10 Kft. The ideal altitude of the WB0 level for severe hail is between 5–9 Kft (Technical Note 98–02). For the non–severe cases, all nine had WB0 heights were above 10 Kft (seven of them above 15 Kft) making melting of the hail highly likely.

The wind type lightning jumps also showed a different but equally distinct pattern, which shows the CG lightning activity to be the primary factor behind the jump. In the 20 wind type jumps, 18 (90% of the time) showed the CG activity always increasing while the IC would increase or remain steady. Usually the IC was increasing with the CG as was the case in 12 of those 18. Given that wind type lightning jumps occurred at the same time there were severe wind signatures on the radar, it stands to reason 12 of the 19 (63.15% of the time) severe wind events directly followed wind type of lightning jumps while only two of the severe wind events occurred after a hail type

jump. The remaining seven followed a mixed type jump. The two wind events that were preceded by a hail type jump also occurred within six minutes of a hail event. The mass of falling hail may have been a strong contributing factor in the wind production for these two events. The findings of the wind type lightning jump indicate a strong tendency for CG lightning to be increasing more rapidly than the IC lightning.

The mixed type lightning jump had an even distribution of types of severe weather occurrences following them, so it is difficult to make any definite assumptions about them. What can be concluded from these cases is the mixed type lightning jump can produce all three types of severe weather; hail, wind and tornados. In this study, the mixed type lightning jump preceded two of the five tornados while the wind type preceded two tornados and the hail type preceded one tornado. The tornado sample is too small to determine if the mixed type is the preferred type of jump for tornados. However, three of the five tornado events followed lightning jumps in which CG lightning activity decreased or ceased similar to the hail type jump. A study that captures more tornado events would be needed to confirm this hypothesis. The fact that CG lightning decreased or ceased during tornado events was a similar finding from previous studies during violent (F4–F5) tornados and during the Hesston, Kansas F5 event (Perez et al. 1997; Steiger et al. 2007a).

This thesis also shows that thunderstorms, both severe and non–severe will produce lightning jumps, which is similar to previous studies (Williams et al. 1999; Goodman et al. 2005; Shultz et al. 2009). This thesis took a slightly different approach in classifying lightning jumps by looking at the rate of increase relative to the thunderstorm's overall lightning activity producing more than one lightning jump threshold. Using more than one threshold to classify a lightning jump, all 34 thunderstorms in this thesis produced lightning jumps and in some cases, identified a jump as much at five minutes earlier in low lightning activity cases. This thesis also showed that in a low lightning activity thunderstorm, the lightning jumps tended to stand out more than high lightning activity cases. The nature of the jumps in the low lightning activity storms is due to the fact the low lightning activity cases had less lightning overall and as such, the increase in lightning, although smaller in magnitude, is much easier to

notice. The fact the that low lightning activity storms do produce lightning jumps required a reduced threshold for the low lightning activity storms and is justified given that the lightning jumps occurred within 10 minutes of the same significant radar derived changes in intensification and collapse tendencies as the high lightning activity cases. The lower threshold for low lightning activity storms is an improvement over past studies that used high thresholds and would miss severe weather as a result of these higher thresholds (Shultz et al. 2009).

One general trend in lighting activity that was not related to any particular radar signature was that overall lightning activity tended to decrease just before or just after a severe weather event. The fall in lightning activity was especially apparent after wind and hail events. The lightning would then increase again in cases where there were multiple severe weather events. The same behavior was also seen in studies by Steiger et al. (2007a). The sudden decrease in lightning activity could give the forecaster an earlier warning that a storm is falling apart if the trend of decrease is long enough but again would have be confirmed by further radar interrogation.

B. LIGHTNING JUMPS AND RADAR SIGNATURES

1. BWER and MESO Signatures

This thesis showed a strong relationship between the BWER MESO radar signatures. In every case where a BWER or MESO signature was noted, the signature began within 15 minutes of a lightning jump. The close relationship between lightning holes and the BWER radar signature was shown to exist with lightning holes (Goodman et al. 2005; Steiger et al. 2007a). Although lightning holes were not found in this study, the BWER is the result of a very strong updraft in a thunderstorm and previous studies by Rust et al. (1982), Steiger et al. (2007a), MacGorman et al. (2002) and Montanya et al. (2007) suggest the lightning hole results from the updraft being so strong that it creates a mono–charge within the core of the updraft making it void of IC discharges while producing a rapid increase in IC discharges around the core of the updraft. Thus, a lightning jump would be associated with a BWER as found in this study. The relationship between the BWER, lighting holes and lightning jumps provide forecasters

with a new tool for thunderstorm interrogation. Since the lightning jump activity can be monitored for changes in intervals as small as every 30 seconds using Vaisala's LTS2005 software, lightning jumps can easily be identified in between WSR–88D volume scans giving the forecaster a heads up something is changing in the storm and that particular storm displaying the jump should be the first storm interrogated when the next volume scan becomes available. The faster refresh time of the lightning interrogation system could potentially increase warning time by as much as five minutes in ideal cases as the forecaster would not have to look at other storms that may or may not be undergoing as rapid of changes as the one displaying the lightning jump.

2. 55DBz Height, VIL and VIL Density

Of the six radar derived parameters looked at in this study, three showed significant direct relationships with lightning jumps. These relationships also tended to be precursors to the type of severe weather that occurred. The hail and wind type lightning jumps showed strong direct relationships to 55 DBz height, VIL and VIL density. The relationship should not be unexpected since increases in the 55DBz height, VIL and VIL density are known factors to hail production and tend to occur prior to severe hail events while decreases, especially significant decreases in these parameters, tend to occur in a thunderstorm prior to severe winds, especially downbursts (FMH–11, Technical Note 98–02).

It is important to note, that any single parameter alone cannot be used to classify the lightning jump type. The 55DBz heights, VIL and VIL density parameters must be used in conjunction with each other with the lightning jumps. The other three parameters, maximum reflectivity, Echo Top and WGP, although did not show a strong relationship, can also be used but should be used with caution. Since these parameters are already used by operational forecasters, it would not be too difficult for an operational forecaster to note these differences when a lightning jump occurs as they are looking for a BWER signature at the same time.

C. SOUNDING DERIVED INDICES AND LIGHTNING ACTIVITY

1. Stability Indices

It was expected that any one of the stability indices would show little or no relationship on their own, but the SWEAT index did appear to show a little skill. In nearly all of the cases when the SWEAT index was above 300, high lightning activity storms occurred. Only two cases with a SWEAT index above 300 failed to produce a high lightning activity storm, one case produced a significant severe hail event the other case occurred on the same day but failed to reach severe levels. Previous studies found that IC lightning appears to have a strong correlation with cyclonic shear (Steiger et al. 2007a). It is well known the SWEAT index is heavily dependent on cyclonic shear and will indicate a high threat level when there is more cyclonic shear present in the atmosphere. Relationships between elevated charge region, cyclonic shear in the low and mid–levels and CG lightning activity have been shown to be robust (Zeigler et al. 2003; MacGorman and Neilsen 1991). IC lightning's dependence of cyclonic shear likely explains the higher individual skill of the SWEAT index.

Caution is advised as other indices, when used in combination, show better skill than when the SWEAT index is used alone. The SI and LI when used in combination with the SWEAT improved the likelihood of high lightning activity cases. The one significant surprise was the poor performance of the CAPE. Since CAPE is considered a good indicator for hail potential, this shows that lightning activity may have little or no relationship to the amount of potential buoyancy in the atmosphere and more dependent on the mid and upper troposphere dynamics and shear. Again, IC dependence on cyclonic shear gives credence to the surprising skill of the SWEAT index.

2. Mixed Phase Layer, WB0 and -20°C Heights

It was hoped that the thickness of the mixed phase layer would show some correlation between a severe event and the lightning activity. Specifically, the deeper the mixed phase layer (between the WB0 and the -20°C heights), the more likely it would be there would be severe hail and high lightning activity. Unfortunately, this was not the case in this study. The sounding derived parameter did not show any significant

relationship to severe weather or the preponderance to high lightning activity. The poor showing was in contrast to previous studies that showed vertical growth in the mixed phase layer is where the greatest charge separation takes place and thus likely to allow for a preponderance of storms to have a high amount of lightning activity (Williams et al. 1999). It needs to be noted that in all 34 thunderstorm cases, the WB0 height was above 10 Kft. A WB0 height between 5,000 and 9,000 ft is much more preferable and conducive to severe hail occurring at the ground (Technical Note 98–02). The high WB0 height is likely why the mixed phase layer thickness did not show a significant relationship to severe weather in this thesis. When the thickness is compared to the amount of lightning activity these thunderstorms produced, it indicated when the thickness was greater than 10,000 ft; there was a slightly higher number of thunderstorms producing a high amount of lightning activity. Previous studies have clearly shown the presence of frozen hydrometeors is critical to the electrification process and have been shown to produce high IC lightning activity (Williams et al. 1999; MacGorman et al. 2002; Steiger et al. 2007a).

D. PROBLEMS WITH THIS STUDY

The primary problem this study was the small data sample. Although this thesis did produce some clear relationships between total cloud lightning activity, thunderstorm structures and the severe weather they produce, there is not enough data in this study to provide a strong confidence in the findings. Many of the findings will have to be confirmed by later studies that include a significantly larger data sample and tested the same way as in this study.

In addition to the small data sample, the lack of ground truth for the non–severe hail events is troubling. Several cases in this thesis that showed very strong hail signatures on radar but failed to provide any hail observations on the ground or the hail may have been smaller than the severe threshold. The events that had strong hail signatures on radar were intuitively verified with the radar signatures used in current operational settings. Despite the assumptions having well–founded and accepted

precedents, the absence of actual ground truth in these cases leaves the door open for doubt. For this reason, these events were assumed to have hail present but remained in the non–severe category for this study.

E. RECOMMENDATIONS

Given the findings of this thesis and the recognized limitations due to sample size, it is recommended any future study on this subject be a robust multi–year field type study covering a minimum of three years (ideally five) to provide a larger statistical sample. A field study of this length should provide ground truth with regards to non–severe hail and non–severe winds, which may also play a significant role in total cloud lightning behavior. The inclusion of non–severe winds could introduce another significant piece to this puzzle as there was no way to evaluate this aspect of thunderstorm phenomena in this study. Although such a field study is major undertaking, this type of study is required to strengthen the indicated relationships found in this thesis.

This thesis also provides some tools to the operational forecast sector that can be put to use immediately. Among the tools are that lightning jumps do precede severe weather, but also lightning jumps tend to have a specific behavior depending on how their parent thunderstorm is changing. The changes in the thunderstorm at the time of the lightning jumps are identifiable on the WSR-88D. This means the lightning jump can give the forecasters an idea of which cell needs immediate attention when there are many cells active. The use of lightning jumps is not intended to be a standalone technique as this thesis helps to clarify the link between radar signatures and lightning behavior changes. The links can provide an early warning of significant changes occurring in the thunderstorm as the refresh rate of total lightning networks is as fast at 30 seconds while the radar can be as long as six minutes. A good operational forecaster will be able to take these tools, and quickly apply them to aid the forecaster to make a faster warning determination with confidence. To determine this combined approach to improve forecast warning reliability and lead time, an operational forecast verification study should be done.

LIST OF REFERENCES

Baker, M. B., H. J. Christian, and J. Latham, 1995: A computational study o the relationships linking lightning frequency and other thundercloud parameters. *Quarterly J. Roy Meteorological Society*, **121**, 1525–1548.

Boussaton, M. P., S. Soula, S. Couillat 2006: Total Lightning Activity in Thunderstorms of Paris. *Atmospheric Research*, **84**, 221–232.

Carey, L. D., and S. A. Rutledge, 2003: Characteristics of cloud-to-ground lightning in severe and nonsevere storms over the central United States from 1989–1998. *Journal of Geophysical Research*. **108**, 4483, doi:10.1029–2002JD002951.

Deierling W., J. Lathan, W. A. Petersen, S. M. Ellis, H. J. Christian Jr. 2005: On the relationship of thunderstorms ice hydrometeor characteristics and total lightning m easurements. *Atmospheric Research*, **76**, 114–126.

Demetriades, N. W. S., D. Buechler, C. Darden, G. R Patrick, A. Makela 2008: VHR Total Lightning Mapping Data use for thunderstorms Nowcasting at Weather Forecast Offices, Vaisala Inc. 1–5.

Demetriades, N. W. S, J.Y. Lojou, M. J. Martin, M. Pezze 2007: VHF Total Lightning Mapping Network in Tucson: Very First Data Acquired. Vaisala Inc, 1–2.

Goodman, S.J., R. H. J. Christian, W. D. Rust 1988: A Comparison of the Optical Pulse Characteristics of Intra cloudy and Cloud-to-Ground Lightning As Observed above clouds. *Monthly Weather Review*, **27**, 1369–1381.

Goodman S. J., R. Blakeslee, H. Christain, W. Koshak, J. Bailey, J. Hall, E. McCaul, D. Buechler, C. Darden, J. Burks, T. Bradshaw, P. Gatlin 2005: The Northa Alabama Lightning Mapping Array: Recent severe storm observations and future prospects. *Atmospheric Research*, **76**, 423–437.

Hodapp, C. L., L.D. Carey, R. E. Orville 2008: Evolution of radar reflectivity and total lightning characteristics of the 21 April 2006 mesoscale convective system over Texas. *Atmospheric Research*, **89**, 113–137.

Harlin, J. D., T. D. Hamlin, P.R. Krehbiel, R. J. Thomas, W. Rison and D. Shown, 2000: LMA observations of Tornadic Storms During STEPS 2000. Eos, Trans American Geophysics Union, **81** (Fall Meeting Supplemental.) Abstract A52C–25.

Kuettner J. P., Z. Levin, J. D. Sartor 1981: Thunderstorm Electrification—Inductive or Non–Inductive? *Journal of the Atmospheric Sciences*, **38**, 2470–2484.

MacGorman, D. R., D.W. Burgess, V. Mazur, W. D. Rust, W. L. Taylor and B. C. Johnson, 1989: Lightning rates relative to tornadic storms evolution on 22 May 1 981. *Journal of Atmospheric Science*, **46**, 221–250.

MacGorman, D. R., and K. E. Nielsen, 1991: Cloud-to-ground lightning in a tornadic storm on 8 May 1986. *Monthly Weather Review*, **119**, 1557–1574.

Mierles, M. R., Pederson, K. L. Capt., Elford, C. H. MSgt., 2003: *Meteorological Techniques*. United States Air Force Technical Note 98–02.

Montanya, J., S. Soula, N. Pineda, O. van der Velde, P. Clapers, G. Solà, J. Bech, D. Romero 2009: Study of the total lightning activity in a hailstorm. *Atmospheric Research*, **91**, 430–437.

Perez, A. H., L. J. Wicker, R. E Orville 1997: Characteristics of Cloud-to-Ground Lightning Associated with Violent Tornadoes. *Weather and Forecasting*, **12**, 428–437.

Pierce, E. T. 1977, edited by Golde, R. H.: *Lightning Protection*, Vol. 2. *Lightning* Oxford University Press, London, 501–513pp.

Shao X., M. Stanley, A. Regan, J. Harlin, M. Pongratz 2006: Total Lightning Observations with the New and Improved Los Alamos Sferic Array (LASA). *Journal of Atmospheric and Oceanic Technology*, **23**, 1273–1288.

Schultz, C. J, W. A. Petersen, L. D. Carey 2009: Preliminary Development and Evaluation of Lightning Jump Algorithms for the Real–Time Detection of Severe Weather. *Journal of Applied Meteorology and Climatology*, **48,** 2543–2563.

Steiger S.M., R. E. Orville, L. D. Carey 2007a: Total Lightning Signatures of Thunderstorm Intensity over North Texas Part I: Supercells. *Monthly Weather Review*, **135**, 3281–3302.

Steiger S. M., and Coauthors 2007b: Total Lightning Signatures of Thunderstorm Intensity over North Texas Part II: Mesoscale Convective Systems. *Monthly Weather Review*, **135**, 3303–3324.

Uman, M. A. 1987: *The Lightning Discharge*. Academic Press Inc. and Harcourt Brace Jovanovich Publisher, New York, 1–189.

United States Department of Commerce, National Oceanic and Atmospheric Adm inistration, 2006: *Doppler Radar Meteorological Observations, Part D WSR–88D Unit Description and Operational Applications*, FCM–H11D–2006 (FMH–11), Washington D.C., 1–1–4–128.

Williams E.R., S. G. Geotis, A. B. Bhattacharya 1989: A Radar Study of the Plasma and Geometry of Lightning. *Journal of the Atmospheric Sciences*. **46**, 1173–1185.

William E. R., B. Boldi, A. Matlin, M. Weber, S. Hodanish, D. Sharp, S. Goodman, R. Raghavan, and D. Buechler 1999: The behavior of total lightning activity in severe Florida Thunderstorms. *Atmospheric Research* **51**, 245–265.

Zeigler. C. L., E. R. Mansel. D. R. MacGorman, and J. M. Straka, 2003: Electrification and lightning in a simulated supercell thunderstorms. *Proc. 12th International Conference on Atmospheric Electricity,* Versailles, France, International Commission on Atmospheric Electricity.

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